CRANFIELD UNIVERSITY

KATHERINE WOOD

AN AGENT-BASED MODEL SCHEMA TO UNDERSTAND HOW SHOCKS TO THE HOUSEHOLD AFFECT ENERGY CONSUMPTION BEHAVIOUR

SCHOOL OF ENGINEERING

MSc THESIS

Academic year: 2013-14

Supervisor: Prof. Sai Gu

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This thesis is submitted in partial fulfilment of the requirements for the degree of MSc by Research.

Abstract

There are many factors which are understood to affect domestic energy consumption, including: occupant demographics such as age, income and family type, occupant attitudes, peer networks and occupant-building interactions such as window opening, heating and lighting patterns.

Both top-down and bottom-up modelling approaches have been used previously to represent these behavioural factors and other domestic energy usage variables such as dwelling construction. Top-down models were found to lack the granularity and flexibility to accurately portray the UK domestic energy sector from the perspective of individual households. Conversely, bottom-up models were found to be more applicable to behavioural factors due to their ability to model individual entities and interactions. However, it was also identified that most current models only consider building construction or occupant behaviour, with few combining the two.

This project aims to combine occupant behaviour and dwelling construction variables by suggesting an agent-based model implementation schema to provide insight into the domestic energy consumption system, with special interest in the effects of life-stage changes on the household and the effect of peer networks on the adoption of energy efficiency measures. Five 'shock' groups are considered, namely, households affected by a recent: retirement, unemployment, new child, house move or reduction in household size. A pilot survey was conducted in order to obtain results to inform model design decisions and the results are discussed.

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List of Abbreviations

ABM Agent-Based Model (Modelling)

DECC Department for Energy and Climate Change

LSOA Lower Super Output Area

OOP Object-Oriented Programming

UML Unified Modeling Language

1 Introduction

The UK Government's commitment to the Climate Change Act 2008 means that UK carbon emissions must be reduced to 80% of the 1990 level by 2050 [1]. Climate change is caused by the burning of fossil fuels which give off harmful greenhouse gases, with carbon dioxide considered the worst. Global CO_2 emissions have increased by approximately 80% since 1970 [2] with predictions suggesting that these will continue to increase in the future from 31.2 Gt in 2011 to 37.0 Gt in 2035 despite energy efficiency measures, and due to the industrialisation of developing countries [3].

An equally pressing concern for the UK government is the depletion of staple energy reserves such as coal and North Sea oil and gas, signifying a gap in UK energy security and leading to an increased need for imported fossil fuels [4]. In order to combat this effect the government needs to move to more sources of 'home-grown' renewable energy such as wind and solar power, and an increase in green technologies such as biomass boilers. Figure 1 shows a change in the energy mix since 1970 with some increase in renewables and a shift from solid fuels to natural gas. However, significant action will need to be taken in order to reverse the increase in emissions.

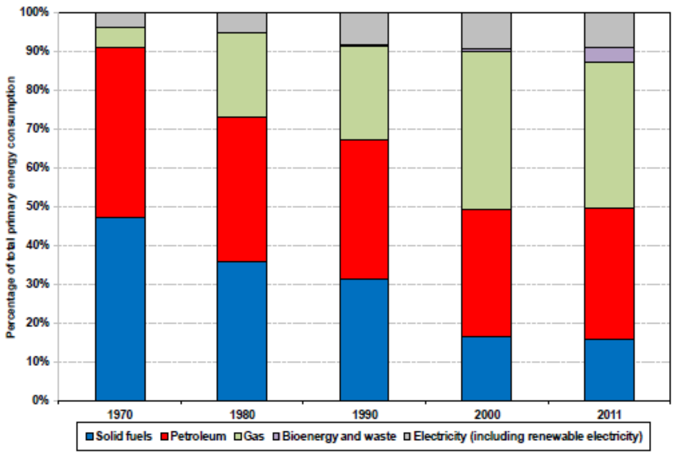

Figure 1: Total primary energy consumption by fuel, UK, 1970 - 2011 [5, pp. 2].

The residential sector currently accounts for around 26% of the total CO_2 emissions for the UK, hence considerable cuts in energy consumption in this area must be effected in order to meet the Climate Change Act target by 2050 [6]. Building construction is seen as a key factor influencing domestic energy consumption, with age being a major determinant since older buildings are more difficult to alter to modern efficiency standards. The size of a property is also a key determinant in energy usage since approximately 60% of energy consumption is used for space heating, thus the larger the property, the more energy is consumed [6].

On the other hand many consider occupant behaviour as the primary influence on domestic energy consumption. This is due to the fact that structurally similar buildings can have highly varied energy consumption [7]. It is attitudinal factors such as having a ‘green’ outlook, demographic factors such as age and income, and occupant behaviours such as lighting and appliance usage patterns that strongly affect energy consumption.

This project aims to understand how occupant behaviours and attitudes change with sudden changes in life-stage (e.g. retirement or having a child) by suggesting an agent-based model schema to represent this scenario. By conducting a survey, the opinions of different demographic groups with respect to which energy efficient and green technologies they are prepared to adopt will be gathered to inform the model. A key interest is the influence of peer networks on the system to suggest which technologies and methods can be used to target potential adopters in these groups.

1.1 Aims and Objectives

Design an agent-based model to:

1. understand how sudden or extreme changes in life-stage affect household energy consumption
2. understand the adoption behaviours of households after life-stage changes with respect to the adoption of energy efficiency measures
3. understand how peer networks can be utilised to promote the adoption of energy efficiency measures.

2 Residential Energy Usage

2.1 Household Energy Consumption Behaviour

The increase in energy demand since the 1970s is largely attributed to changes in lifestyle and comfort standards. Most households in the seventies were comfortable with an indoor temperature of 12°C, wore thicker clothing, had fewer appliances, and generally had no central heating [6, 8]. In today's society, which is swamped by high-energy-consuming devices, energy consumption from the domestic sector continues to rise. We must also consider that there are around 40% more homes now than in 1970 adding significant demand to the energy sector, although newer houses have improved energy efficiency standards [6].

Although a clear reduction in carbon emissions can be achieved through making properties more efficient [6], there is also a significant body of research which concludes that the most influential factor affecting energy consumption is the behaviour of a dwelling's occupants. A prominent study in the 1970s showed that for 28 structurally identical dwellings, energy consumption could vary by up to double across the sample [7]. The study also showed that the consumption of new residents moving into one of the existing properties was not predictable due to variations in occupant behaviour.

In the literature there are three distinct themes related to the effect of occupant behaviour on domestic energy consumption. Firstly, there is a plethora of research into how demographic and sociological factors affect occupant consumption behaviour [9–13]. The focal point for these studies are factors such as age, family type, and income. The second line of research focuses on the interaction of occupants with their dwelling [14–16]. The main considerations here are behavioural patterns such as the occupant usage patterns of windows and lighting. Finally, the effect of occupant attitudes on energy consumption is considered, with some studies categorising occupants into groups dependent on their attitude towards energy consumption practices [17–20]. Clearly all three themes are interrelated by the very fact that they all concern occupant behaviour. In the following sections each theme will be discussed in more detail. However, in order to better understand the context of how energy is used in the average UK home, energy end-uses will be discussed first.

2.2 Energy End-uses

The effect of occupant behaviour on a household's energy consumption is clearly of great impact. However this complex relationship is not easy to define and we must understand the causes for this behaviour before we can define its impact on the household's consumption, hence we will quantify how energy is used in the domestic setting, i.e. energy end-uses (see figure 2).

At 60%, space heating accounts for the largest proportion of total household energy consumption [21]. This implies that those households which either have a larger area to heat (i.e. a bigger property) or have greater comfort requirements will undoubtedly have higher consumption than average. Similarly, older dwellings will have greater space heating requirements due to their inefficiency in retaining heat.

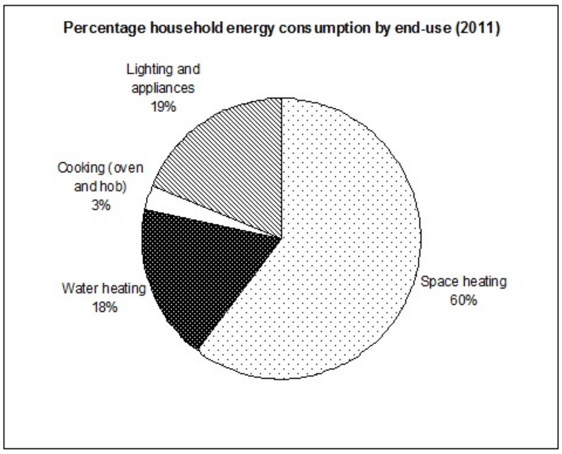

Figure 2: UK Household energy end-use (2011) [21])

The use of lighting and appliances accounts for 19% of household energy consumption [21]. While lighting only accounts for around 3% of the total household energy consumption, it is worth noting the continued increase in consumption since 1970. Although the use of low energy bulbs has become the norm and in fact incandescent bulbs are no longer on sale, it is now commonplace to have atmospheric and decorative lighting, hence households now have many more light fittings than they did forty years ago [6]. The use of appliances has also increased in recent times due to a change in culture and a dependency on electric appliances such as computers and mobile phones for work, study and leisure. Also, advancements in technology mean we are now more dependent on appliances for the daily running of a household, for example by using washing machines, dishwashers, fridges and freezers, and for leisure activities such as TVs and digital equipment, radios and games consoles [6].

The third greatest consumer of energy in the home is water heating which is responsible for 18% of the total [21]. Although water heating is a significant contributor to household energy consumption, the Department for Energy and Climate Change (DECC) has shown through modelling UK energy trends that this percentage has been reduced from 30% since 1970. It attributes this reduction to efficiencies in modern heating systems including the installation of combi boilers, more prolific use of electric showers and a reduction in heat loss from water tanks with better insulation of pipes [6].

The final energy end-use to consider is cooking (this excludes cooking appliances such as microwaves which fall into the appliances category). Due to efficient cooking methods such as fan ovens and again cultural changes which have seen much less cooking from scratch and an increase in ready meals, the total energy use from cooking is just 3% [6, 21], hence it has a much less profound affect on household energy consumption than the previous categories. We can consider, however that occupants whose lifestyle involves a lot of cooking or inefficient use of the hob and oven will have a greater energy consumption in this area than the average household.

2.3 Research Theme 1: Occupant Demographics

Some view household characteristics and occupant demographics as key influences of domestic energy consumption [9, 11]. The three most significant factors found in the literature, namely household type, occupant age, and household income, are discussed below.

2.3.1 Household Type

The effect of household type (i.e. whether the household consists of a single person, a single parent, a couple, a couple with children, or multi-adult household) can have a considerable effect on energy consumption. In a study of 300,000 Dutch homes, Brounen et al. concluded that although gas was highly dependent on dwelling characteristics, especially the age of the dwelling, social characteristics also play an active part in the variation of gas and particularly electricity consumption across households. They found that single households use the least amount of energy, with families with children consuming the most (see figure 3) [9, 10]. Although intuitively gas consumption will be greater for larger households since they generally live in larger houses than single people, they found that the gas consumption per head reduces by 26% for each additional family member, so per head, single households use a far greater amount of gas than larger households [9]. This could be attributed to the fact that the primary use of gas in the home is for space heating, hence the house would be heated to the same capacity whether there is one resident or many. A similar effect is seen with electricity consumption.

These findings are consistent with work done by BRE Group in 2005 on English households, who also consider multi-person households such as house-shares which

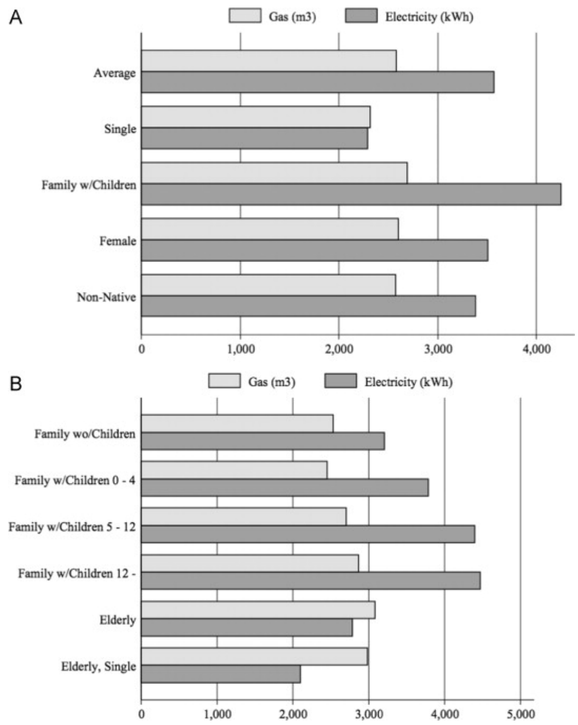

Figure 3: Annual energy consumption in Dutch households (A) consumption by family type and (B) consumption by family cycle [9, pp. 936].

represent only 7% of the sample. These households interestingly have the lowest gas consumption but the greatest electricity consumption of all households with two or more adults [22]. This could be due to the fact that the occupants are living as individuals within the building rather than as a family unit such that they are cooking and using appliances such as televisions individually.

2.3.2 Occupant Age

Occupant age is one of the most significant factors affecting energy consumption, not only due to the fact that elderly people have higher comfort requirements but also due to the fact that requirements and daily activities change as the life stages of families progress. It has been shown that a couple aged 60 or over use around 8% more gas than a couple under 60 [22], which is no doubt due to the fact that the average retired couple will spend more time in the home and may have the house heated to a higher temperature [10]. It is also worth noting that a single person aged 60 or over uses a vast 30% less gas than their coupled counterparts. Yamasaki and Tominaga also stated that due to the ageing populations of many western countries the issue of increased comfort requirements, and hence energy consumption may become more prevalent in the future [13].

The reverse is true for electricity consumption, in fact a couple under 60 years

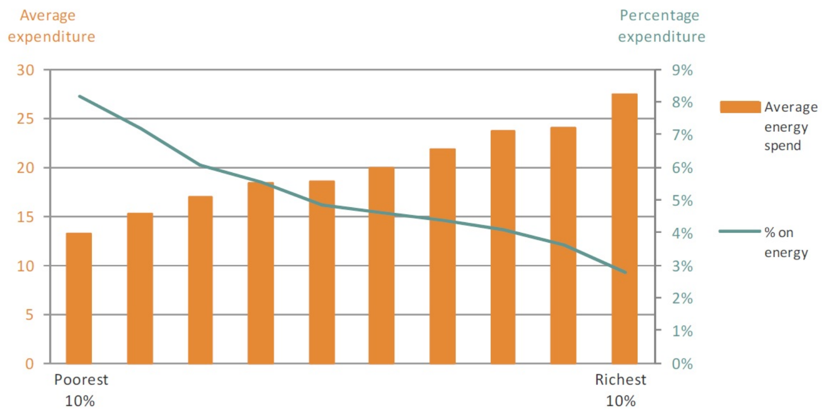

Figure 4: UK weekly fuel expenditure by income decile (£/wk/household) 2010 [6, pp. 29].

old use nearly 30% more electricity [22]. This is more than likely due to the fact that the elderly will have less high energy-consuming gadgets and appliances [9].

It is also interesting to note from Brounen et al.'s research that households with children use more energy in general but for electricity usage in particular, a steady increase in consumption can be seen as the children get older (figure 3). The authors have playfully dubbed this the "Nintendo-effect" since teenage children spend more time watching TV, playing on games consoles and using high-energy-consuming devices [9].

2.3.3 Household Income

The relationship between energy consumption and income is a complex one. As you would intuitively expect, the amount a household spends on energy increases as income increases. However, it is also true that poorer households spend a higher percentage of their income on fuel. Figure 4 shows data from a report by DECC which splits households into ten deciles according to their income. The paper highlights the fact that although the wealthiest households spend £3.50 more on energy per week, this equates to just 2.8% of their income, whilst the poorest decile spend on average 8.1% of their income on energy (since this is averaged data it does not show those households who spend 10% or more of their income on energy, i.e. those in fuel poverty) [6]. The reason for this behaviour is attributed to the fact that lower income households may have less disposable money to improve their homes using insulation and energy efficiency measures while the reverse is true for high income families although they may also be less aware of their energy use.

Brounen et al. found when considering the effect of income on energy consumption, that electricity consumption is highly dependent on income and with an increase in disposable income of just 1% the electricity consumption increases by 11%. A less pronounced effect was seen for gas consumption [9].

Cayla et al. acknowledge income as the most important social factor affecting energy consumption. In their study of French households they found, consistently with previous research, that energy consumption increases with income, however, they found three distinct consumption groups in the data. The first was the poorest 30% of households whose expenditure on energy was at a constant level since they were constrained to pay a minimum amount to ensure their standard of living. The second group comprised the middle income families which spent more on energy as their income increased in order to reach their satisfied comfort level, and the final group were the top 20% of earners where the amount spent on energy plateaued as their comfort levels were met [11]. This is in line with previous work which identified middle income households as more receptive to price changes [23].

2.3.4 Other Factors

In addition to the factors mentioned above, there are many other demographic factors which affect domestic energy consumption, notably employment status, dwelling tenure [24] and working from home [12, 25], but these will not be discussed further here.

2.4 Research Theme 2: Occupant-building Interaction

In many domestic situations and especially in office buildings, heating, cooling, lighting and ventilation are all centrally controlled. It has been found that for buildings that are not managed in this way that the occupants' usage of building controls can lead to a varied effect on energy consumption [14], so much so that simulations of occupant use of building controls have been created to understand this behaviour [16]. Andersen et al. showed that window opening behaviour and heating use was strongly linked to external temperature, but also that the occupants' perception of their environment with respect to noise level and illumination affected window opening and lighting usage respectively, especially with respect to gender [14].

In a study of 72 UK dwellings, Firth et al. considered the effects of different electrical appliances on energy consumption [15]. By categorising appliance usage according to different appliance groupings (continuous and standby, active, and cold appliances), they identified appliances which are left plugged in or on standby as an area which can be improved upon in order to conserve energy since no function was being served by leaving them on. Due to significant variations across structurally similar buildings, with the lowest annual consumption for a monitored dwelling being 902 kWh and the highest being 7743 kWh, they concluded that building construction had little impact on electricity usage.

2.5 Research Theme 3: Occupant Attitude

The final research theme covers the effect of occupant attitude on domestic energy consumption. In some studies in this area residential energy users are categorised according to certain criteria relating to their 'green' attitude. In a government report by DEFRA seven categories were devised according to people's "willingness and ability" to act in a pro-environmental way [26]. These were positive greens, waste watchers, concerned consumers, sideline supporters, cautious participants, stalled starters and honestly disengaged. This document aimed to give policy insight into finding barriers preventing each of these groups from adopting a greener outlook. In the same vein Zhang et al. categorised energy users into eight similar categories in order to conceive of a framework that could be used for local level policy making [27].

An individual's attitude towards energy may not reflect their actual behaviour. Valkila and Saari found that people's perception of their own energy use is not representative of their behaviour, with some having a greener attitude than their behaviour would suggest; the attitude-behaviour gap. This was acknowledged as due to the fact that comfort was more important in their lifestyles [28]. They also noted that residential area was related to energy attitudes, with different districts having different environmental outlooks. The most densely populated area had the greenest attitudes.

Energy awareness can also be considered a barrier to reducing energy consumption. A study sample of approximately 1700 Dutch households showed that only 56% of participants knew the cost of their monthly energy bills; those with a greener outlook were more aware of their energy consumption [17]. Although energy efficiency measures are available, this technology is redundant if consumers do not even consider it. It is clear that an increase in energy awareness must be effected before attempting to reduce energy usage.

It is also evident from the literature that social norms and peer pressure can lead to increased pro-environmental behaviour. It has been shown that sharing individual consumption data between peers can lead to a heightened awareness of energy consumption, with a greater effect being seen with a larger network [18]. Behaviour change is more prevalent in those in a negatively perceived situation compared to the norm. It has also been shown that behaviour change can be continued after study periods by maintaining contact with neighbours or friends who are part of the same scheme [29].

The effects of peer networks on domestic energy consumption is well documented. It has been seen that communication between consumers regarding individual perceptions of products informs a household's decision as to whether to adopt energy efficiency measures. There is also evidence that technologies which are visible such as photovoltaics had an increased effect on adoption rates [23, 30, 31]. Of course, individuals have many routes of information such as mass media and marketing, however, McMichael et al. suggest that respondents in their study indicated that households were equally likely to consult all of these sources; in fact information gained via a peer network reduced their uncertainty [30], with the strength of the relationship also having an effect [23]. It is hoped that this phenomena will be captured in the model, hence providing a better understanding of how these networks can be used to target willing individuals.

Although peer networks contribute to a households decision as to whether to adopt a technology, there are also other factors, drivers and barriers that each household will consider before arriving at a decision. Bale et al. define this as function of perceived utility and barriers to adoption [32].

3 Residential Energy Modelling

In the UK and abroad there is now a significant importance placed on energy consumption, and with 26% of UK emissions and approximately 30% of global emissions coming from the domestic sector there is a necessity to make substantial reductions here [33]. This has inevitably led to a huge body of research into the area and there have been many different modelling techniques used to further understand the problem. However, Swan and Ugursal still describe the area as “an undefined energy sink” due to the vast difference in building construction, the variability of occupant behaviour, and difficulty in obtaining accurate household survey data due to the invasion of privacy [33].

In their recent paper which introduces a model paradigm for modelling residential energy by defining consumer archetypes, Zhang et al. define three current research trends from the literature. The first utilises statistical methods to define major factors affecting energy usage. The second considers how pro-environmental behaviour and changes in behaviour can reduce consumption. The final area considers the energy loads of dwellings and what causes variation in load patterns [27]. In the review they discuss energy models from each of these areas, however we will only consider the first two since they are most relevant to the research topic.

Reviews of current energy models from the literature almost universally define two key modelling paradigms; the top-down and bottom-up approaches [27, 33–35]. Figure 5 shows different top-down and bottom-up approaches. Top-down models view the residential energy sector and sometimes whole energy infrastructure, usually at a national level [27], as a single functioning entity as if it is being viewed from above. It does not distinguish end-uses or individual consumer behaviour but uses historical data in order to predict future patterns in the energy system from a high level, such as in terms of energy supply and demand. These models saw widespread use in the wake of the 1970s oil crisis in order to better understand and predict the UK energy sector [33]. A fundamental weakness in the approach is the dependency on historical data, meaning future technological advances cannot be predicted and by omitting individual energy usage, can neither be analysed [33].

Bottom-up models take a more granular approach. They consider individual entities within the system such as individual dwellings or structurally similar dwellings and then weight the samples to represent local or national emissions [33, 34, 36]. In the literature there is a clear focus on dwelling construction, this is due to the fact that as yet there are few bottom-up models which attempt to understand the relationship between occupant behaviour and energy consumption [37], most likely

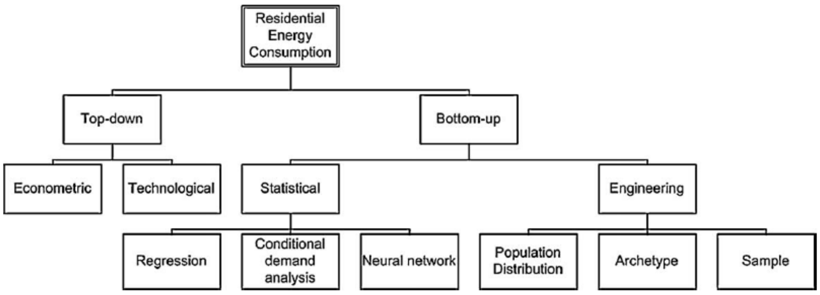

Figure 5: Top-down and bottom-up modelling techniques for estimating the regional or national residential energy consumption [33].

due to its complex nature. Similarly, top-down models can neither represent this due to their aggregated approach. Nonetheless, although widely acknowledged to be far more data intensive than the top-down approach, Swan et al. attribute one of the key benefits of bottom-up modelling as the ability to model the effect of occupant behaviour on energy consumption [33].

A relatively new field of bottom-up modelling is that of agent-based modelling (ABM) which is at present rarely used in residential energy research. It allows individual entities (or agents) to be modelled such that their behaviour is independent, but their interactions with each other and their environments can represent a complex system. This project will use ABM as a modelling paradigm (see Section 4 Agent-Based Modelling).

4 Agent-based Modelling

4.1 Background

Agent-based modelling is a bottom-up modelling technique, many have tried to define the term agent-based model but definitions vary greatly across the field. The most clear, concise and intuitive definition found in the literature is given by Railsback and Grimm in their recent book; *Agent-Based and Individual-Based Modeling: A Practical Introduction*, and goes as follows:

> "ABMs are ... models where individuals or agents are described as unique and autonomous entities that usually interact with each other and their environment locally. Agents may be organisms, humans, businesses, institutions, and any other entity that pursues a certain goal. Being unique implies that agents usually are different from each other in such characteristics as size, location, resource reserves, and history. Interacting locally means that agents usually do not interact with all other agents but only with their neighbors-in geographic space or in some other kind of "space" such as a network. Being autonomous implies that agents act independently of each other and pursue their own objectives .... Agents therefore use *adaptive behavior*: they adjust their behavior to the current states of themselves, of other agents, and of their environment." [38, pp. 10].

In more simplified terms an agent can be described as a well-defined entity, which acts for its own means and whose interaction with other agents and its environment, may lead to its own adaptive behaviour and/or cause a global effect. Agents exist in a global environment and usually communicate across networks and neighbourhoods, i.e. with other agents within a close proximity.

Due to their flexible nature, ABMs have been implemented across many disciplines such as economics [39], social sciences, biology, anthropology and more. However, some call for the collaboration between disciplines in order for agent-based modelling to reach its full potential [35]. An early example of an ABM, although created using pen and paper, is Thomas Schelling's segregation model. This model showed the dynamics of a system where individual counters had a preference of the same coloured neighbour. Each time the system progressed, more distinct areas of colour emerged [40, 41]. Other principal models include Conway's Game of Life in which simple patterns of counters on a chess board follow three simple rules based around the birth, survival and death of a counter dependent on the state and position of its neighbours [42], and Axelrod and Hamilton's Prisoner's Dilemma [43]. Here two prisoners have the option to either defect or cooperate, but each person's decision is dependent on the other's action. The punishment is different dependent on the outcome, but neither individual knows the other's decision before they make their own. These simple models represent the crux of the ABM paradigm where each agent acts individually for its own means, but in combination with other agents can cause a global effect.

4.2 Suitability to the Problem

Agent-based modelling has been compared to the familiar object-oriented programming (OOP) approach since both revolve around the use of well-defined entities and their interactions. From a software design perspective the two approaches are quite similar, however, when it comes to implementation there are clear differences. Objects must be triggered by a message before they take action, whereas an agent is permanently active. Also, agents are adaptive so can alter their behaviour in order to meet their needs, but objects only act according to pre-defined methods [44].

From a computational perspective, computers are now powerful enough to cope with the large computational power that complex ABMs require. This is because agents can become numerous and constant updates of their state and interactions must occur throughout the model execution [45].

Due to its bottom-up approach and ability to model complex, interacting systems, agent-based modelling is a suitable paradigm for this project. Key benefits of using this method are that: the problem can be split into easily maintainable segments that can be altered individually such that the whole model is not affected; some less important parts of the model can be simplified whilst others can have a high level of detail [46]; and interactions and relationships can be modelled (a key consideration when modelling social phenomena).

In their review of energy models Keirstead et al. recognised the opportunities presented by using the agent-based modelling bottom-up approach. However, they also indicate potential pitfalls with using this approach [47]. When implementing complex models assumptions will inevitably be made in order to represent a whole system. These assumptions should be made clear and in order to test them the technique of 'backcasting', which uses historical data to validate that the model outcome is representative, can be used [36]. The extensive, quality data required for such models is also a necessary consideration, hence a suggested survey format is put forward in section 10 in order to obtain this data. In a similar vein, in their paper Ma and Nakamori create three simplified energy system models in order to compare the benefits of several approaches [48]. They identified that traditional optimization models are computationally small and although agent-based models are more based on assumptions, that agent-based models allow adaptive behaviour and decision-making to be represented. Their final remark is that these methods should not compete but each satisfy a different aspect of research. Bale et al. also suggest that with energy systems being complex systems with interacting entities for which specific behaviours cannot be predicted, current modelling paradigms such as the prominent scenario based MARKAL model [49] fall short of the low-level detail which ABMs can provide [35].

4.3 Agent-based Energy Models

Although agent-based modelling is a relatively new concept in the Energy field, there have been several models created to try to represent energy consumption. Theses include Durana et al.'s model of the physical energy network [50], a model for optimising the performance of wind-photovoltaic energy storage and power-generation [51] and Natarajan et al.'s model of domestic energy consumption [52].

A model related to the one defined in this document by Lee et al. analyses UK domestic energy consumption [36]. The model, which considers a household's willingness to adopt an energy efficient technology, suggested that when subsidies for insulation were not available the uptake was greater due to the fact that potential savings were more significant. The limitation of this study is that it only considers homeowner households due to tenanted households relatively limited ability to adopt energy efficiency measures. However, as they state that this only represents approximately 67% of UK households, it is not then representative of the general population. They also suggest that their findings are a result of using an agent-based model due to the emergent properties observed.

A social network model by Bale et al. to observe adoption behaviours, considers the willingness to pay decision-making processes of households. This model also assumes tenanted properties are unable to adopt and that information passing occurs via a network of friends and family [32]. The model described here will use proximity for communication in the network in the first instance rather than family or friends due to the findings of Bollinger et al., whereby visual technologies in a neighbourhood had the greatest adoption rates [31].

As shown here, there have been several ABMs in the field of domestic energy consumption, however none consider the changes to household life-stage or shocks defined in this project.

4.4 Agent-based Modelling Platforms

Although agent-based modelling is a relatively new field there are a wide range of both open source and proprietary modelling platforms to choose from. For a newcomer to the area it can be quite a task to decide which platform is most suited to their needs and abilities, since although many platforms seek to be 'generic', they are restricted by that fact that they were written for a certain purpose or field. The current ABM platforms available can generally be categorised into two groups: the first are platforms which use the 'framework and library' structure [53]. These contain ABM concepts which can be implemented using a library of functions and includes the platforms; Repast [54] and MASON [55]. The second, are GUI based platforms such as NetLogo [56], which uses its own simplified programming language and is better suited to users with limited programming experience since they can partially construct models using the user interface [53].

In this project the AnyLogic platform [57] which combines both a user friendly interface and the flexibility to customise models by adding Java code is suggested. The platform uses state charts which are similar to flow diagrams to describe the actions and states of each agent type, this structure allows for the quick re-design of models.

5 Contribution

As has been seen in the literature, both occupant behaviour and building construction have a pronounced effect on domestic energy consumption, however there are few models that successfully consider both [58], probably due to the differing modelling approaches used for each area. Current energy modelling research revolves around building construction and there are few models of occupant behaviour due to its complex nature [27]. Equally, studies that do consider occupant behaviour do not consider how drastic changes to the lifestyles of the occupants will affect their energy consumption behaviour and patterns.

This project aims to approach both of these shortcomings by putting forward an agent-based model schema for domestic energy consumption to better understand how life-stage changes affect household energy usage patterns and to observe the effects of a peer network on the system. A pilot survey specification will be given in order to obtain data on the behaviour of certain demographic groups such as the recently retired or unemployed, to ascertain which, if any, changes have been made to accommodate a new lifestyle and hence to inform the model.

The following section describes briefly the 'shocks' or life-stage changes that will be considered in the project. Each shock has been selected due to its profound effect on the 'status quo' of the household's daily running such that energy consumption behaviour change is likely.

5.1 Life-stage Changes

- **Unemployment**: The household will see a potentially significant reduction in income. The unemployed individual may be at home more frequently, thus increasing the household's energy consumption and bills. This shock is particularly important due to the current economic climate in which the UK has 7.8% unemployed and 20.7% of 16 to 24 year olds out of work (May 2013) [59].

- **Retirement**: A considerable reduction in income will occur and it may be the case that both wage earners retire at the same time, hence the change will be felt more. It must also be considered that there will be a vast increase in the amount of time the occupants spend at home, especially in the winter months, thus impacting their energy consumption and bills. Finally, it is often the case that the elderly generation have a higher comfort level and would have the house heated to a greater temperature.

- **New baby**: Although during the maternity period for most households there may be little loss of income, there are new pressures such as increased energy consumption from spending more time at home. There will be new requirements which also consume more energy such as keeping the baby warm, fed and properly cared for.

- **New home**: Each household will have different energy requirements from their previous property which may result in an increase or decrease in energy consumption dependant on building structure and size. It may also be a necessary or convenient time to replace some of their energy infrastructure such as insulation, double glazing or boiler; this may be an inexpensive energy efficient boiler or they may opt for a more expensive green technology such as a biomass boiler.

- **Reduction in size**: If a divorce, bereavement or child leaving the family home occurs then the energy requirements of the household will change and in the first two instances the household income may reduce significantly.

6 Identification of Significant Model Parameters

After reviewing the current literature on domestic energy consumption with particular emphasis on occupant behaviour and demographics and dwelling construction, the variables identified as significant factors in this system have been coordinated into tables 1, 2 and 3. These refer to environment variables, dwelling parameters and occupant parameters respectively, in order to justify their inclusion or exclusion in the model. Most notably the individual appliance usage patterns have been excluded due to the huge scope of this one area and the difficulty in obtaining adequate data to represent this accurately. These variables will form the basis of the household and dwelling agents' definitions. The most significant factors are given here, of course there are many other factors which also affect residential energy usage.

Table 1: Environment variables affecting domestic energy consumption

Parameter	Significance
Cost of energy	People generally adapt to small price increases but consumption, and hence demand, reduces when there are large price increases [23].
Energy supply	Factors influencing the supply of energy to the household affects how much the energy service costs [60]. This will be excluded from the model since by default this effect is considered in the cost of energy variable.
Peer network	Sharing information between study participants about average usage data has a greater effect on energy reduction than giving feedback in isolation or none at all [18]. Word of mouth is important in the promotion of energy efficiency measures, especially visible ones such as PV. Information is passed on through friends, organisations and through neighbours, hence proximity is important [30–32].

Table 2: Dwelling parameters affecting domestic energy consumption

Parameter	Significance
Dwelling age	Strong effect on gas consumption. Older buildings have greater consumption with up to 65% variance. Buildings built after 1980s are much more efficient due to changes made as a result of the 1970s oil crisis [9].

Table 2: Dwelling parameters affecting domestic energy consumption

Parameter	Significance
Dwelling type (detached house, apartment etc.)	Detached and semi-detached properties use more energy than terraced houses and apartments. Exposed surfaces and generally larger size means more energy is needed for the same thermal comfort [9].
Number of occupied rooms	The greater the number of heated rooms in the dwelling, the greater the gas consumption [10, 12]. Consider this instead of dwelling size since some rooms may not be heated.
Tenure	Owner occupied homes use far more energy, but electricity usage is higher in rental properties as more do not have gas [22]. Rental properties less able to adopt as can't alter property [32, 36].

Table 3: Occupant parameters affecting domestic energy consumption

Parameter	Significance
Appliance usage	Appliance usage patterns such as number and length of showers, number of fridges, time television is on per day all affect energy consumption [10]. Since this could cover a considerable number of additional variables, the scope is too vast and granular to consider in the model at this stage.
Attitude	Four significant factors found which link energy consumption and attitude: personal comfort and health, high-effort-low-payoff, perception of energy saving impact, and belief in energy crisis [7]. Energy awareness is most influenced by conservation attitude and is also only partially determined by demographics. Those with a greener outlook are more aware of their energy consumption [17].
Energy-saving appliances	Energy efficient appliances lead to reduced energy consumption [61]. Energy efficient boilers and heating systems lead to reduced gas consumption. DEFRA study showed 71% of respondents looked for energy saving logo when purchasing appliances [62].

Table 3: Occupant parameters affecting domestic energy consumption

Parameter	Significance
	Lower income households don't have access to funds to buy energy efficient appliances which would reduce their bills [11].
Home during day	Elderly occupants spend more time at home causing increased gas consumption [10]. Working from home also has a strong link to increased energy consumption. [12]
Household culture (male-headed, female-headed, non-native etc.)	Slight increase in gas consumption for female-headed households and a slight decrease for non-native households [9]. Both negligible effects, hence will not be included in the model.
Household income	A 1% increase in income leads to an average 11% increase in spending on electricity [9]. Higher income is linked to a larger dwelling and hence greater space heating requirements. Higher income households also have a higher internal temperature [10]. Less access to capital means lower income households don't have the resources to buy energy-saving appliances to reduce their bills [11]. Elderly households generally have lower income but higher comfort and living requirements. Older study participants with higher income choose higher comfort levels [13]. Poorest 10% of households spend more than 11% of their disposable income on energy whilst richest spend less than 2% [24].
Household type (single occupant, couple with children etc.)	Households with children consume the most energy and single adults the least. Electricity consumption greatly increases when there are children in the household. Gas consumption is slightly increased with the number of occupants (but an economy of scale can be seen for large households) [9, 24]. Single households use double the amount of gas per head than households with children, and elderly households use 31% more with single elderly households using much less than their married peers. [9]. Increased heating and lighting usage in elderly households [13].

Table 3: Occupant parameters affecting domestic energy consumption

Parameter	Significance
	Impact of children is little until teenage, then electricity consumption increases [9]. Households with children consume more energy in space heating and heavy duty appliances such as washing machines, tumble dryers and occupants are generally absent during the day [10].
Internal temperature	Elderly households have higher thermal comfort requirements [9,13].
Knowledge	Energy literacy is largely related to education and not attitude, and both energy literacy and awareness are not related to conservation behaviour, hence will not be included as a model variable [17].
Number of appliances	Strong effect on electricity consumption. Households with more high-energy-consuming devices have greater electricity consumption [9]. Active appliances such as washing machines, kettles etc. use the largest proportion of electricity consumption rather than standby and cold appliances [15]. Difficult to find a data source on the number of appliances in different household types, hence in the model we can instead use indicators such as the number of children (who use more appliances than adults [9]) to show an increase in electricity consumption.
Number of occupants	Strong correlation to energy usage - more for electricity consumption than for gas consumption. Since space heating remains the same irrelevant of the number of occupants per capita usage is less for larger households. Economy of scale [9,24].

6.1 Variable Interactions

Further to identifying which variables are significant factors affecting domestic energy consumption from the literature, it is also important to identify if and how these interact in order to apply these relationships to the model. Figure 6 shows a condensed view of important relationships identified between key variables (the full interactions table is given in Appendix C), these should be used as a basis for the model relationships. Interactions coloured orange signify variables with increasing functions, and the blue interactions symbolise decreasing functions. Others marked in black are more complex with the most significant are defined in the diagram.

As we have seen from the review of current literature, income, household type and occupant age are all key factors affecting energy consumption. However, it is clear that there are many complex relationships which affect energy consumption in the household, these relationships will not be discussed further here since they were covered in detail in section 2.

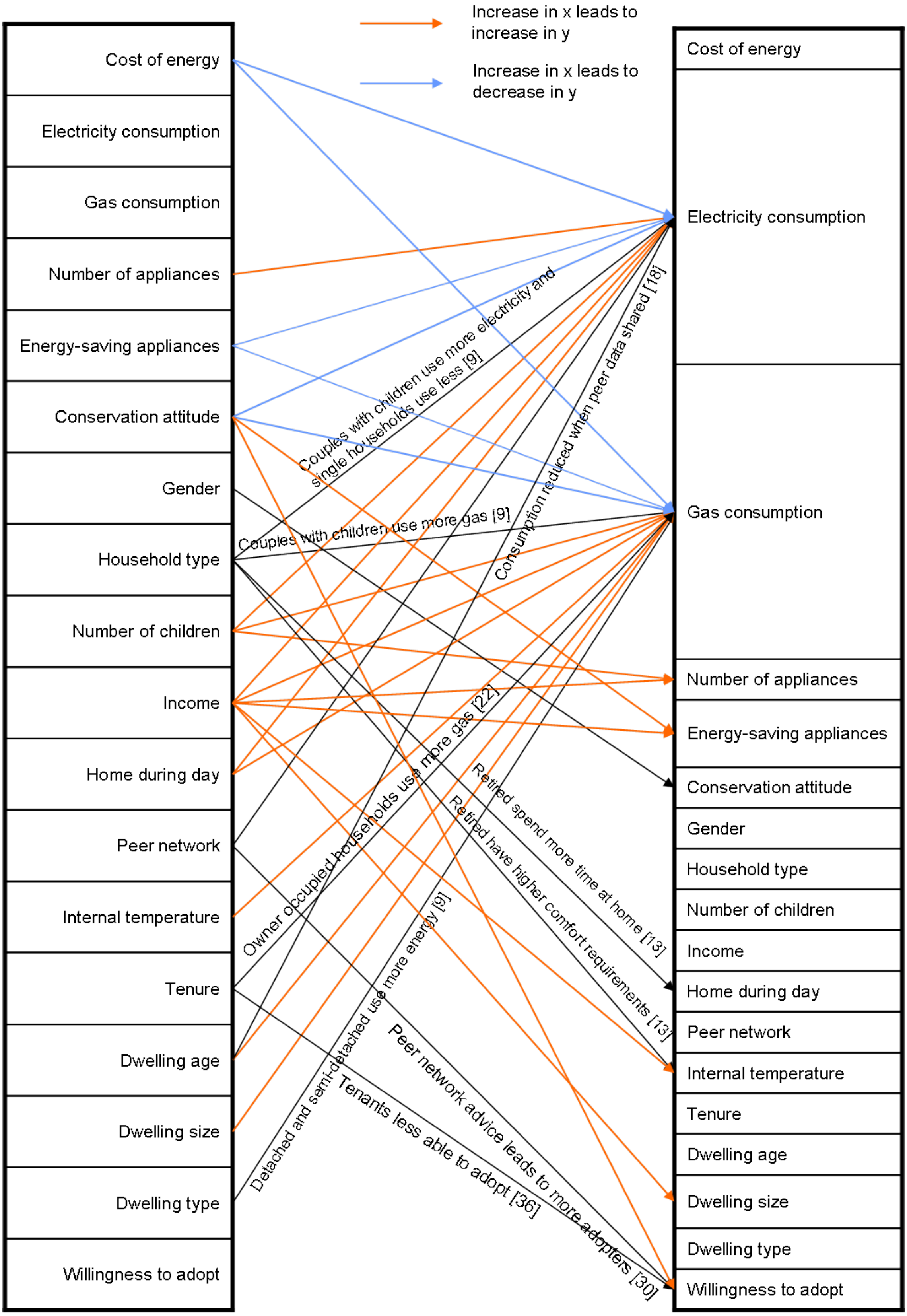

Figure 6: Simplification of interactions of energy consumption variables found in literature.

7 Method

As with all model development the design and development process of agent-based models is not linear. Instead iterative development both at the design phase and the implementation and testing phases is fundamental in order to obtain the most accurate and valid results. Figure 7 shows the model design and implementation process that should be followed in order to create a well designed and structured agent-based model of domestic energy consumption. The work flow is based on the author's own previous software development experience and is in line with software engineering work flows documented in the literature [63–65].

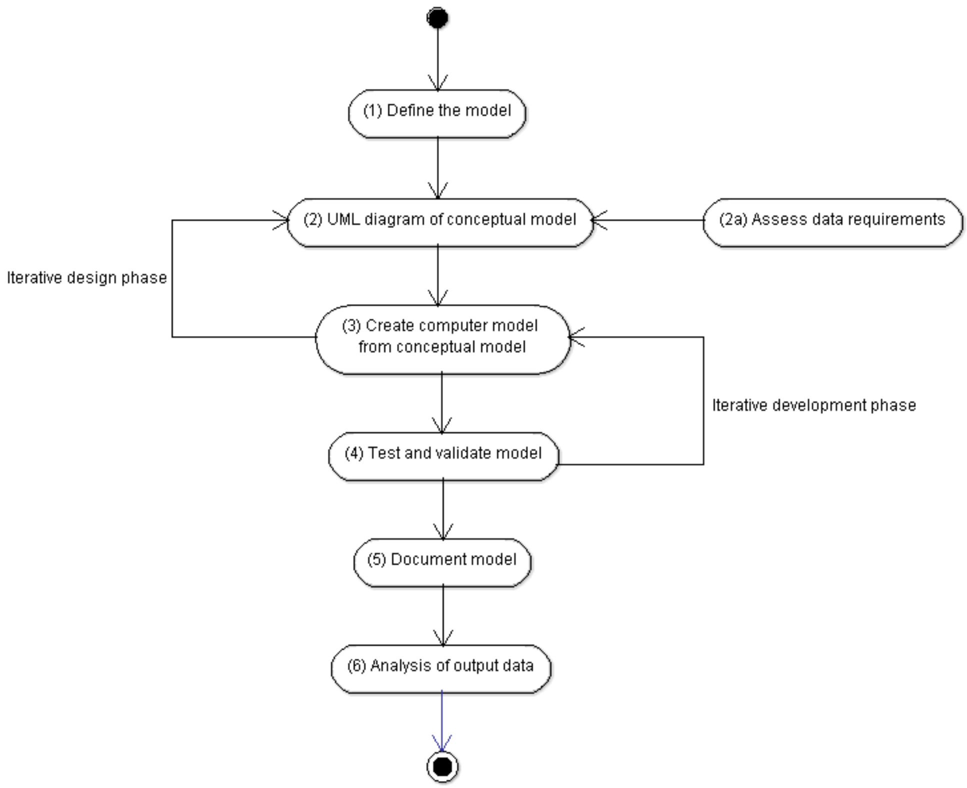

Figure 7: Model design process

The diagram may at first appear simplistic, however each self-contained part requires detailed and intensive work. In the following sections each correspondingly numbered object in the flow diagram will be elaborated upon to define the modelling process more explicitly.

7.1 Defining the Model

As with software development, the first stage of the model development cycle is an accurate specification. This specification should make clear the aims, purpose, and requirements of the model as well as constraining the model (at least for the first version) such that it is implementable [63, 64]. A key benefit of defining the model is that it can be used throughout development as a reference point to keep the model in line with the scope and aims of the project, without diverging into other areas before the model is complete.

The model in this project will be defined using the ODD protocol. This method was defined by Grimm et al. for the exact purpose of defining agent-based models when they found a distinct lacking in a standard procedure for describing models that could be transferable between disciplines and modellers [38, 66, 67].

Overview	Purpose
	State variables and scales
	Process overview and scheduling
Design concepts	Design concepts
Details	Initialization
	Input
	Submodels

Figure 8: The seven elements of the ODD protocol, which can be grouped into the three blocks: Overview, Design concepts, and Details [38].

The final document, which will be completed after implementation and testing, should contain enough detail that models can be re-implemented by different developers. Figure 8 is taken directly from their paper defining the standard and highlights the main sections that should be included in the document.

7.2 Conceptualising the Model Using UML

The Unified Modelling Language (UML) should be used to create a blueprint for the model that will be implemented in the software by using flow diagrams (or in the UML terminology *Activity Diagrams*). From experience of using these tools previously, the primary benefit of creating a conceptual model before implementation is that it is not fixed and does not take long to create. This allows the developer to completely re-write the model several times before a first version is settled upon [63] without much time loss to the project. Secondly, and almost as critically once a model design has been agreed, the UML diagram will provide an excellent platform for explaining the model to colleagues and other interested parties. In his book on software engineering, Schach advocates the use of UML as a design tool which has become somewhat of a standard in OOP [65] and hence is suitably applicable to agent-based modelling.

7.2(a) Assessing Data Requirements

Assessing a project's data requirements before implementing a model is imperative. Until the developer fully understands exactly what data is required for their model they cannot begin to implement it. It may be discovered that the data required for the model does not exist or is not of a high enough quality to use and the project must be postponed until such data becomes available. Conversely, the developer will probably only have a vague idea of the data required for the model before the model is conceptualised in a diagram, hence as shown in Figure 7 processes (2) and (2a) are concurrent and stage two cannot be contemplated until both are adequately developed. See section 10 for specific data requirements for the project.

7.3 Implementing the Model

The model should be implemented in AnyLogic as stated in section 4.4, which due to its simple graphical interface makes creating initial models quick. With the software being a Java based language the model is customisable by the developer unlike less flexible platforms such as NetLogo which uses its own language. To create a model in AnyLogic a state chart can be created which will mimic a functional version of the UML diagram created in step two.

Processes two and three are part of an iterative design phase. As the developer implements the model it may be discovered that initial conceptual ideas are in fact too difficult or unreliable to implement in the software or in fact there is a better way of doing something. This may mean that the model design can be reassessed, and the definition tweaked several times during implementation before the first version of the model is complete [63].

7.4 Testing and Validating the Model

There are two specific avenues of model testing and both must be executed in order to achieve a robust and reliable model. These two processes combined are known in software engineering terms as verification and validation. Validation ensures that the model works as anticipated, hence mainly concerns the correct programming of algorithms such that when tested the results are as expected. Verification on the other hand checks that the model conforms to the original specification document [38, 63]. Although during the modelling process the specification of the model may change slightly as the model progresses, as stated above, the specification should still match the resultant program since it should have been incrementally altered throughout the design process.

As shown in Figure 7 the testing phase is part of the iterative development phase. The model testing will be iterative in two senses: firstly since testing should be done in increments as model 'milestones' are completed before implementation is continued. Secondly, the final testing phase once the model is complete is iterative as bugs will inevitably be found in the model, this may cause a rethink of how certain parts of the model are implemented.

As has become a standard in agent-based modelling, a sensitivity analysis should be conducted once the model is complete [47, 68]. This involves determining which model input parameters have the greatest overall effect on the model and allows the modeller to either justify or re-model this. This process is done by running the model many times with different input for one parameter in order to observe the effect and then repeated for all variables of interest [53].

7.5 Documenting the Model

Although information documenting the model's progress should be kept up to date throughout the design and implementation process [65], a document explaining the model and how it works should be completed as part of the model development process. This will inform any future testing and/or debugging of the model but will also serve as a manual for explaining the model to other colleagues. A revised version of the ODD protocol defined in step one, with any changes to the design during implementation included, can be used as part of the model documentation.

7.6 Analysing the Output Data

The model should be analysed using a combination of sensitivity analysis as discussed above and by statistical analysis of output from the model. Correlation and regression analyses can be conducted in order to ascertain the prevalence of model parameters and interactions.

8 Model Definition Using the ODD Protocol

The model will be defined using the ODD protocol designed by Railsback and Grimm [38, 66, 67] as discussed in section 7.5. This will provide a blueprint for the model such that it is implementable in the future and satisfies the following aim:

An agent-based model schema to understand how shocks to the household affect energy consumption behaviour and the adoption of energy efficiency measures.

8.1 Overview

8.1.1 Purpose

To utilise the flexibility of a bottom-up agent-based modelling approach which considers both occupant behaviour and dwelling characteristics to gain insight into how life-stage changes, such as moving house or a member of the household retiring, affects the energy consumption of a household, and whether, as a result, the uptake of energy efficiency measures can be promoted to these households. We refer back to the project aims:

- Do life-stage changes within a household have an impact on their energy consumption?
- Under what conditions are households more likely to change their energy consumption behaviour and/or adopt energy efficiency measures?
- How can peer networks be utilised to promote the adoption of energy efficiency measures?

8.1.2 Entities, State Variables and Scales

The entities and state variables to be included in the model are discussed briefly below however a more comprehensive definition of each can be found in tables 4- 7, with algorithms where possible, aimed at facilitating future implementation of the model. These may be updated as new information becomes available.

Entities and State Variables

The entities in this model are households, dwellings and patches of land. Each household will represent the demographic characteristics, attitudes and most importantly energy usage patterns of the occupants living within it. This may not necessarily be a family unit, it could also be a group of individuals living together as part of a house share for example.

The dwelling entity represents variables which define physical properties which can affect energy consumption, for example, dwelling age, dwelling type and floor size. Households may move between dwellings upsizing and downsizing depending on the life-stage of the household and shocks/life-stage changes scheduled as part of the model. For the first iteration of the model the end of life of the dwellings is not considered due to the fact that this would add an added level of complexity which may not be imperative to understanding domestic energy consumption.

Finally, the patches (abstract physical locations) include variables which define the local area such as dwelling density thus giving the model the flexibility to represent different urban and rural geographical locations based on the initialisation of the model. Patch variables will be specified in hectares, in line with the government units for dwelling density [69].

Environment

There are additional variables to consider which affect all households alike. These are global or environment variables. In this model scenario we consider economic factors such as inflation, the cost of energy and the cost of installing energy efficiency measures.

Scales

The simulation should run for 5 years with monthly ticks. This period has been selected since we are concerned with understanding the current residential energy sector rather than predicting future trends however, this period may be extended if necessary. Monthly ticks have been deemed granular enough since significant changes to a household do not occur very frequently and also a household may reassess its energy requirements on a monthly basis.

8.1.3 Process, Overview and Scheduling

The processes that each entity will be subject to are discussed in brief here. For more precise details refer to tables 4- 7.

The first step is to calculate the electricity and gas consumption for each household based on any changes which occurred in the last time-step such as a household's decision to adopt a new technology.

Then each household's characteristics will be assessed and then potentially a shock will be assigned to the household. This is dependent on individual shocks since retirement is more relevant to older occupants and the inverse is true for having a baby. Shocks will be assigned to a proportion of agents defined by user input probabilities for each shock by randomly shuffling agents which meet the requirements for that shock. Once a household is given a shock it cannot be given the same shock for at least one year (twelve ticks). After this the frequency of a shock will depend on the user probabilities given.

After shocks have been assigned any parameters which need updating as a result should be done here. This will include the number of children, number of adults, dwelling location etc. Also, aging variables such dwelling age and occupant age should be updated here annually (every twelve ticks).

The final step should be to adjust any environment variables ready for the next time-step, such as inflation and energy cost, although these should only be updated every quarter (four ticks).

No shocks will be applied in the first time-step in order to allow consumption variables to be updated after initialisation.

8.2 Design Concepts

8.2.1 Basic Principles

The basic principles of the model are defined in section 8.1.1.

8.2.2 Emergence

The emergent behaviour we expect to see in this model are the global trends in energy consumption as the model progresses and the uptake (or lack of uptake) of energy efficiency measures. This outcome would result from a combination of current inflation, the proximity and frequency of visible energy efficiency measures owned by neighbours, income and other factors.

8.2.3 Adaptation

Households in this model are able to adapt to changes in their environment. Households have to adapt their behaviour dependent on increases/reductions in income, inflation, cost of energy and shocks.

8.2.4 Objectives

The main objective of a household agent is to increase its disposable income. This means minimising expenditure such that they reach a comfortable equilibrium between reducing expenditure on essential items and maintaining a constant or better level of comfort. To a lesser extent an agent is motivated by status. In this model an agent's decision to adopt a green technology such as photovoltaics, which can be seen as a status symbol, because a neighbour has [30, 32], becomes a distinct behaviour.

8.2.5 Learning

In the first iteration of the model none of the model agents can learn from previous experience.

8.2.6 Prediction

Whether a household agent decides to adopt an energy efficient technology by deciding whether the gains outweigh the barriers is a prediction based on the assumption that if they choose to adopt then they will get either a financial benefit or increase in comfort, or if they choose not to adopt, that the perceived risk or barriers outweigh the gains.

8.2.7 Sensing

It is only household agents in this model that have any sensitivity to their environment. Households are sensitive to global variables which affect their income such as changes in inflation or the cost of energy. Household agents can also sense whether other households on the same patch have installed energy efficiency measures.

8.2.8 Interaction

Household agents interact with each other directly. A household which adopts a new energy efficiency measure can affect the decision of another household within its vicinity to adopt a similar technology such as photovoltaics [30, 32]. A household can only have an affect on other households within the same patch. Dwelling agents can neither interact with each other nor household agents.

8.2.9 Stochasticity

Several of the model parameters will be defined by probabilities given as user inputs via the user interface. This means that the model is not fixed and that external factors can affect the outcomes. These include: for each of the shocks, the likelihood of a household being given a shock and the percentage of empty dwellings in the model.

8.2.10 Collectives

There are no collectives (aggregations of agents) in this model.

8.2.11 Observation

In order to make sense of the model dynamics we need to include the following observations, all represented on the model display:

- a time series graph of the average electricity consumption
- a time series graph of the average gas consumption
- a time series graph of the global adoption rates for energy efficiency measures
- indicators for the percentage of households that have had a 'shock' in the last year (last four time-steps), i.e. percentage of households with: an unemployed occupant, a child less than one year old, a recently retired occupant, one or more less occupants, or a new dwelling.

8.3 Details

8.3.1 Initialisation

The initialisation of the model variables is given in tables 4- 7.

8.3.2 Input Data

Historical data used to inform model parameters such as; inflation, energy prices and installation costs can be read in from an input file, these parameters can then be updated from the file in order to represent historical trends.

8.3.3 Submodels

The following tables define any submodels which should be included in the model. The aim is to give an overview of the inner workings of the processes which occur in the model. These are initial algorithms which can be changed due to design and implementation decisions made by the programmer. Where possible survey data gathered specifically for this model (to be defined in section 10), will provide representative data of the area being studied. If this is not possible then alternative potential data sources have been specified. Variables with non-numeric values have been represented by an index instead.

At each time-step the electricity and gas consumption for each household should be calculated using a module that implements the BREDEM model calculations with model input parameters. This model is well documented and used in practice hence should provide reliable estimates [70]. Where necessary input parameters are not available, a representative value may be used instead. For example, the BREDEM model requires information on dwelling fabric, which is not included in the model, hence a standard dwelling stock profile could be used to provide these values.

Some assumptions have been made in order to reduce the complexity of the model for the first version, these are:

- the child bearing age is between 16 and 42
- income increases in line with inflation
- the household is given an attitude based on the head of the household
- a dwelling is affordable if the cost is less than five times the households income
- a household's income per capita reduces by 40% on retirement
- a household's income per capita reduces by between 30% and 70% on unemployment or a reduction in size.

Table 4: Model environment variables

Variable	Description	Initialisation	Scheduling	Submodel	Data Source
Electricity cost	pence / kWh	From input file	Quarterly	Updated to next value in input file	Quarterly energy price (UK Govt.) [71]
Gas cost	pence / kWh	From input file	Quarterly	Updated to next value in input file	Quarterly energy price (UK Govt.) [71]
Inflation	Percentage inflation rate	From input file	Quarterly	Updated to next value in input file	ONS Consumer Prices Index [72]
Installation cost	Installation cost of available energy efficiency measures	From input file	Static	N/A	Energy Saving Trust installation costs [73, 74]
Payback period	Payback period for available energy efficiency measures	From input file	Static	N/A	Energy Saving Trust payback periods [73, 74]

Table 5: Model patch variables

Variable	Description	Initialisation	Scheduling	Submodel	Data Source
Dwelling density	Number of dwellings per hectare (DPH)	43 (based on UK Govt. new dwelling average)	Static	N/A	Land Use Change Statistics in England: 2011 [69]
Number of patches	Number of patches in the model	Based on model location (e.g. size of urban Bedford = 2354 hectares (patches))	Static	N/A	Key Statistics for Urban Areas in England and Wales [75]
Patch size	Size of a model patch	1 hectare = 100m x 100m	Static	N/A	

Table 6: Model dwelling entity variables

Variable	Description	Initialisation	Scheduling	Submodel	Data Source
Dwelling age	Integer (years)	Distribution based on data source	Annually	`dwellingAge = dwellingAge + 1`	English housing survey 2012: profile of English housing report [76]
Dwelling empty	Boolean. Is dwelling lived in	Based on user input probability	Monthly	Triggered by movedHouseShock	N/A
Dwelling type	0 = Converted flat 1 = Purpose-built flat 2 = Detached house 3 = Semi-detached house 4 = End of terrace house 5 = Terraced house 6 = Semi-detached bungalow 7 = Detached bungalow	Distribution based on data source	Static	N/A	English housing survey 2012: profile of English housing report [76]
Number of heated rooms	Integer	Distribution based on data source	Static	N/A	Survey data
Tenure	0 = Owner occupied 1 = Private rented 2 = Local authority 3 = Housing association	Distribution based on data source	Static	N/A	ONS Key Statistics: Housing and accommodation [77]

Table 7: Model household agent variables

Variable	Description	Initialisation	Scheduling	Submodel	Data Source
Attitude	Scale 1 - 5 of conservation attitude with 5 being the most concerned.	Distribution based on data source	Static	N/A	Survey data
Electricity consumption	kWh / month	N/A	Monthly	Calculate using BREDEM model [70]	Model input
Gas consumption	kWh / month	N/A	Monthly	Calculate using BREDEM model [70]	Model input

Household type	0 = Couple with no children
	1 = Couple with children
	2 = Single parent with children
	3 = House-share
	4 = Single person
		Distribution based on data source	Monthly	Triggered by newChildShock and householdReductionShock
				`// Couple household`
				`if (newChildShock AND`
				`(householdType == 0 OR`
				`householdType == 1)){`
				`householdType = 1`
				`// Single household`
				`} else if (newChildShock AND`
				`(householdType == 2 OR`
				`householdType == 4)){`
				`householdType = 2`
				`}`
					ONS Families and Households, 2013 [78]

Table 7: Model household agent variables

<table>
<tr><th>Variable</th><th>Description</th><th>Initialisation</th><th>Scheduling</th><th>Submodel</th><th>Data Source</th></tr>
<tr><td>Income</td><td>Total household income per year</td><td>Distribution based on data source</td><td>Annually</td><td><pre>householdIncome = householdIncome * inflation
if (newChildShock == true) {
   // Reduce income to Maternity Pay (SMP)
   if (monthsSinceShock <= 2) {
       income = origIncome * 0.9
   } else if (monthsSinceShock >= 3 AND
                 monthsSinceShock <= 12) {
       income =
       min(origIncome * 0.9 AND threshold)
   // After 1 year assume back on full pay
   } else {
       income = origIncome
   }
}
// Retirement leads to 40% income reduction
if (retirementShock == true) {
   income = (income / numAdults) * 0.6
}
// Unemployment and reduction in size leads
// to one adult not contributing to household
// income
if (unemploymentShock == true OR
    householdReductionShock == true) {
       contribution = income / numAdults
                              * rand (0.3,0.7)
       income = income - contribution
}</pre></td><td>ONS Wealth and Income, 2010-12 [79,80]</td></tr>
</table>

Table 7: Model household agent variables

Variable	Description	Initialisation	Scheduling	Submodel	Data Source
Internal temperature	Integer (°C)	Distribution based on data source	Quarterly	Based on survey data	Survey data

Move house shock	Boolean	N/A	Monthly	`if (rand <  userInputProbability AND`
				`householdReductionShock == false){`
				`moveHouseShock = true`
				`// New house must have min num rooms`
				`for each (shuffled empty dwelling){`
				`if (dwellingValue < income * 5 AND`
				`minNumRooms > numHeatedRooms){`
				`moveHere`
				`}`
				`}`
				`} else {`
				`moveHouseShock = false`
				`}`
					N/A

New child shock	Boolean	N/A	Monthly	`// Adults must be of child bearing age`
				`if (averageAdultAge <= 42  AND`
				`averageAdultAge >= 16 AND`
				`householdType != 4 AND`
				`rand <  userInputProbability AND`
				`newChildShock == false) {`
				`newChildShock =  true`
				`} else {`
				`newChildShock = false`
				`}`
					N/A

Table 7: Model household agent variables

Variable	Description	Initialisation	Scheduling	Submodel	Data Source

Number of children	Three integer variables for the census age bands:
	Band 1: 0 - 4 years
	Band 2: 5 - 11 years
	Band 3: 12 - 18 years
		Distribution based on data source	Monthly	Triggered by newChildShock
				`if (newChildShock == true) {`
				`    numChildren04 = numChildren04 + 1`
				`}`
					ONS Families with Dependent Children, 2011 (QS118EW) [81]

Number of adults	Integer	Distribution based on data source	Monthly	Triggered by householdReduction-Shock
				`if (householdReductionShock == true) {`
				`    numAdults = numAdults - 1`
				`}`
					ONS Families and Households, 2013 [78]

Reduction in house-hold size shock	Boolean	N/A	Monthly	`if (rand <  userInputProbability AND`
				`  householdReductionShock == false) {`
				`    householdReductionShock = true`
				`} else {`
				`    householdReductionShock = false`
				`}`
					N/A

Table 7: Model household agent variables

Variable	Description	Initialisation	Scheduling	Submodel	Data Source

Retirement shock	Boolean	N/A	Monthly	`// Adults must be of retirement age`
				`if (avgAdultAge >= retirementAge AND`
				`    retired == false AND`
				`    retirementShock == false AND`
				`    rand < userDefinedProbability) {`
				`       retirementShock = true`
				`} else {`
				`       retirementShock = false`
				`}`
					N/A

Work from home	0 - 5 days / week	Distribution based on data source	Monthly	`if (rand <  userDefinedProbability) {`
				`      workFromHome = true`
				`} else {`
				`      workFromHome = false`
				`}`
					ONS 2011 Census Analysis - Distance Travelled to Work [82]

Table 7: Model household agent variables

Variable	Description	Initialisation	Scheduling	Submodel	Data Source

Unemployment shock	Boolean	N/A	Monthly	`if (unemploymentShock == false){`
				`if (rand < userDefinedProbability){`
				`unemploymentShock = true`
				`} else {`
				`unemploymentShock = false`
				`}`
				`} else {`
				`// If unemployed then random number`
				`// generated each step decides whether`
				`// employed again or not`
				`if (rand < anotherUserDefinedProbability){`
				`unemploymentShock = false`
				`}`
				`}`
					N/A

9 Conceptual Model

Step two of the method defined in section 7 requires the model to be conceptualised in a diagram. The model diagram has been created following the same theme as the behavioural model Van Raaij and Verhallen define for residential energy use (figure 9), where circular elements represent factors which can be utilised to reduce energy consumption.

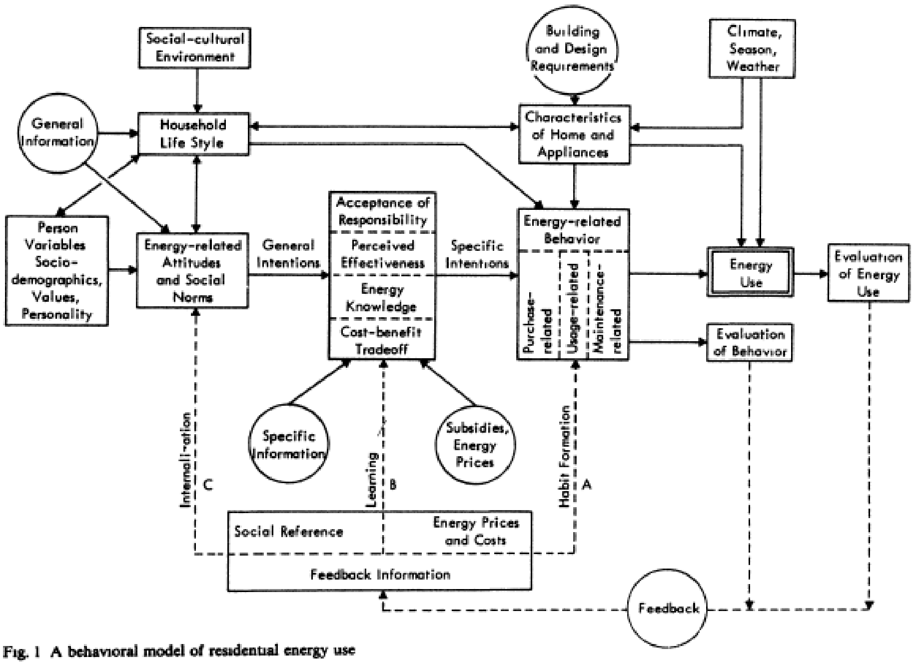

Fig. 1 A behavioral model of residential energy use

Figure 9: A behavioural model of residential energy use [23]

The conceptual model shown in figure 10 visualises the model described in the last section. The three model entities: environment, household and dwelling are shown with significant factors affecting residential energy consumption. As we have seen in the literature, these three entities combined have a significant effect on domestic energy consumption and by considering them together in an agent-based model it is hoped that a better understanding of how these factors, along with peer networks affect adoption rates can be achieved. In the model a household considers all factors and then evaluates their energy consumption, weighs up the costs and benefits of adopting an energy-efficiency measure and then decides whether or not to adopt. This decision-making process then feeds back into the peer network as a new household which can inform others. This includes the decision not to adopt since this particular household deemed that the benefits did not outweigh the disadvantages at the present time. If a household chooses to adopt energy-efficiency measures then the dwelling entity is duly updated.

The shock factor is shown in a broken box since the effects of such on energy consumption are not yet known and for which insight from the implemented model is hoped to be gained.

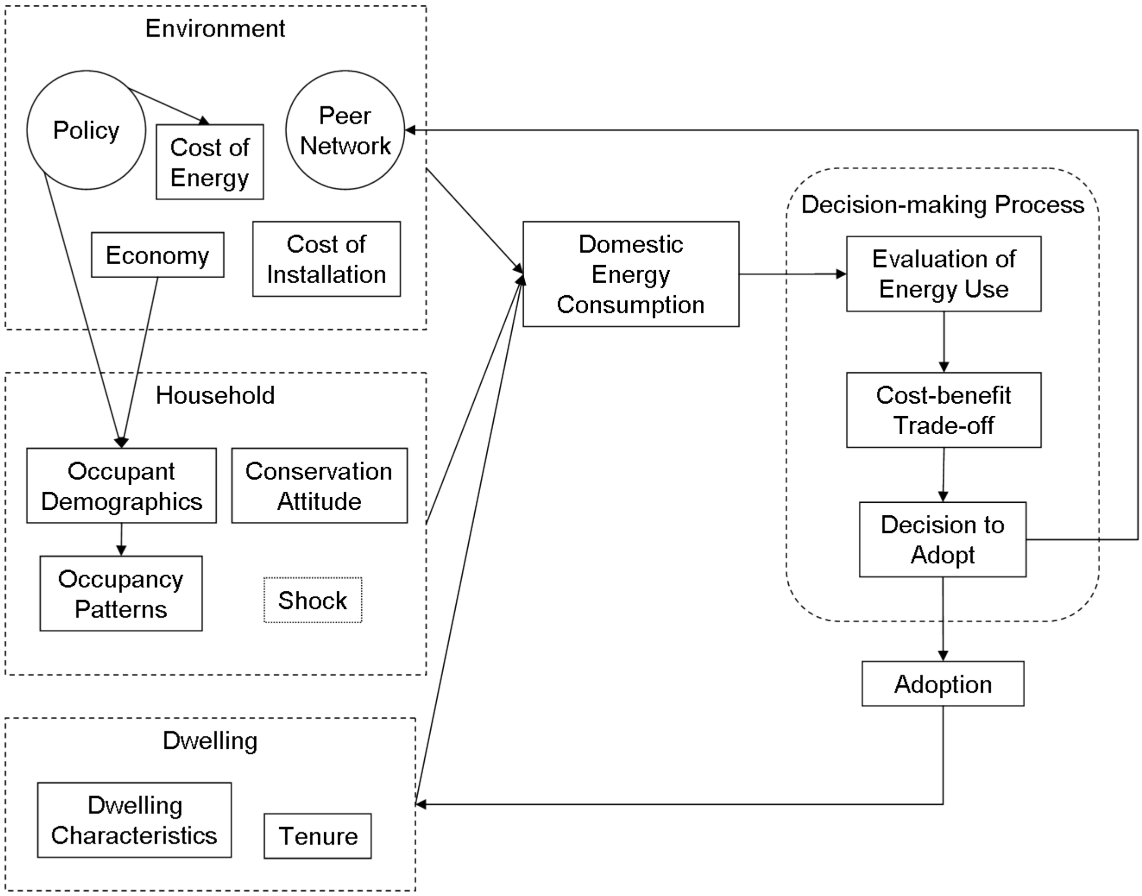

Figure 10: Conceptual model for domestic energy consumption

10 Data Requirements

As has been seen in the current literature, a significant drawback of using agent-based models is the extensive data requirements [35, 47], with Bale et al. stating after implementation of their model on the diffusion of technologies across social networks, that more data was required before further development could continue [83]. In order to combat this, the data that will be used as input parameters for the model will be from surveys of the community and 2011 Census data. The benefit of using census data for some variables is that the data is freely available and has comprehensive demographic information such as family type, size and age for very specific and well defined geographical areas (*Lower Super Output Areas* (LSOAs)) of between 400 and 1200 households [84]. The down side however, is that the census data does not contain information about household income since this was deemed too intrusive for several reasons during a pilot survey [85]. This is where survey data can be of great value since although a participant may elect not to answer a direct income question, other questions such as employment status and role can be used as markers.

A key benefit of using survey data is that it will be tailored to the exact purpose of its collection. A pilot survey was conducted in order to better understand the type of questions that were effective or ineffective in obtaining the data required to inform the agent-based model, with special interest in questions relating to household 'shocks'. The following sections define the pilot survey that was undertaken for this study (included in Appendix B) and the results obtained.

10.1 Pilot Survey Instrument

10.1.1 Survey Design

Prior to the distribution of the survey, ethical consent to conduct the research was acquired from SEREC in accordance with University guidelines (see Appendix A). The opening paragraph ensured participants' anonymity, provided informed consent and gave contact details for future reference. For paper surveys a return envelope was provided.

The tables defined in section 6 which contain significant domestic energy consumption parameters were used to inform the questions included in the survey in order to obtain the model input data required. Questions aimed at obtaining data relating to the five 'shock' groups specified in section 5 (recently moved house, had a new baby, retired, became unemployed or reduced in household size) were also included. More detailed information on these scenarios will allow the model to be more refined to each group's attitudes and energy practices and hence less assumptions to be made.

The questions were formatted in Likert Scale (both from positive to negative and negative to positive in order to prevent predictability of questions), frequency and free text. Table 8 gives the question themes included in the survey.

Table 8: Survey question themes

Theme	Question Number
Attitudes	1, 3
Knowledge	2
Building characteristics	4 - 6
Energy usage	7 - 10
Shocks: evaluative probability	11 - 14
Willingness to adopt	15 - 18
Shocks: subjective probability	19
Demographics	20 - 25
Feedback	Back cover

Positive statements to assess both environmental and economic attitudes were included in order to prevent leading questions. The boundaries for demographic questions were based on the 2011 Census data categories such that either source can be used if data is missing [86], and the questions gathering data on willingness to adopt were informed by the literature [87]. The survey was conducted with a psychology student who had previous experience in survey design.

10.1.2 Sample

Both an electronic and paper version of the survey were distributed to opportunity samples. The electronic survey was emailed to a sample of staff and students at Cranfield University. Although this gave information on varying incomes, demographics and dwelling characteristics it also made the sample biased towards highly educated households and a high proportion of house shares than is representative of the population. The paper survey was conducted in a village in order to reach more elderly and less technologically literate participants. This had the advantage of covering a different geographical location but was also an opportunity sample hence not fully representative of the population.

10.2 Pilot Survey Results

For the paper survey a response rate of 30% (9/30) was obtained and the electronic version rate being 32% (16/50) with two electronic surveys disregarded as they were received empty. This meant that the overall sample size was 25 participants.

Figure 11 shows that the modal age of all adult occupants in each household was between 26 and 35 but there were also 15% of occupants between the ages of 66 and 75 which aligns with the last census report [88], hence the sample is representative of households both of working age and retirement age which needs to be considered for the change in life-stage to retirement.

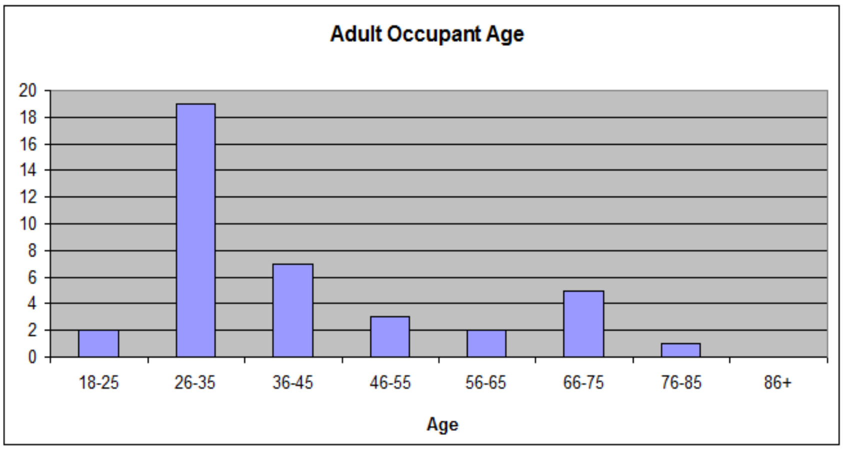

Figure 11: Adult occupant age

The income demographic (figure 12) shows that the majority of respondents had a household income of less than £10 000 per annum. This result is likely to be skewed due to the high proportion of students and retired households hence is not representative of the general population.

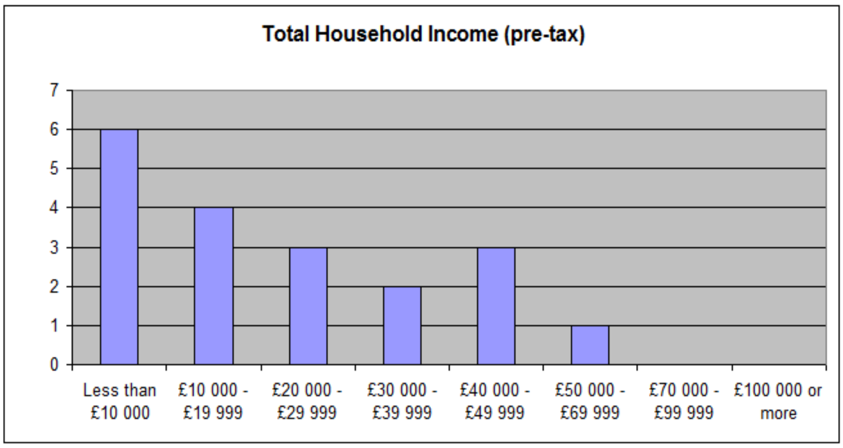

Figure 12: Total household income

The spread of households was fairly distributed with 30% of households being a couple without children, 22% a couple with children, 22% single person household, 22% house share and just 4% were single parent households. These results were not in-keeping with the UK trend for which 56% of households are couples with children and just 3% are house shares [89]. This is most likely due to the high proportion of students and retired couples in the sample.

The results obtained for question 19: *"Would any of the following changes to your household influence your decision to install energy efficiency or green technology measures?"* were important since this informs the investigation of the project aims by looking into the subjective probability of a household considering installing energy efficiency measures after a 'shock' to the household. Interestingly, the results shown in figure 13 suggest that although around 23% of respondents identified moving house as an influence, a considerable 68% of the sample stated that none of the shocks defined would influence them. This may well be the case, however, we should consider that due to the sample size and limitations, a different and larger sample might yield different results.

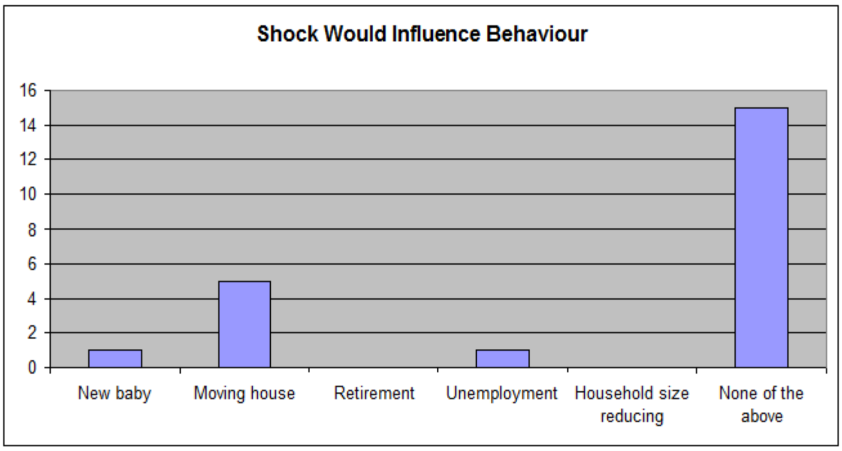

Figure 13: Shock would influence behaviour

Participants were also asked to answer questions on which type of energy efficiency measures they would/would not install, or have already installed. The results (in Appendix D) show that the least favourable measure, with a considerable 57% of respondents who answered this question, would not install micro wind generation. As stated by Caird et al. this could be down to several factors including; cost, insufficient fuel savings, the need for planning permission and the fact that they are deemed visually intrusive [87]. The most subjectively favourable measures were; replacement glazing, photovoltaics and energy efficient boilers. However, the highest frequency technologies which had already been adopted were; loft insulation, efficient hot water systems and external wall insulation. To understand this difference between subjective and evaluative probability the main barriers and drivers for installing energy efficiency measures are discussed below.

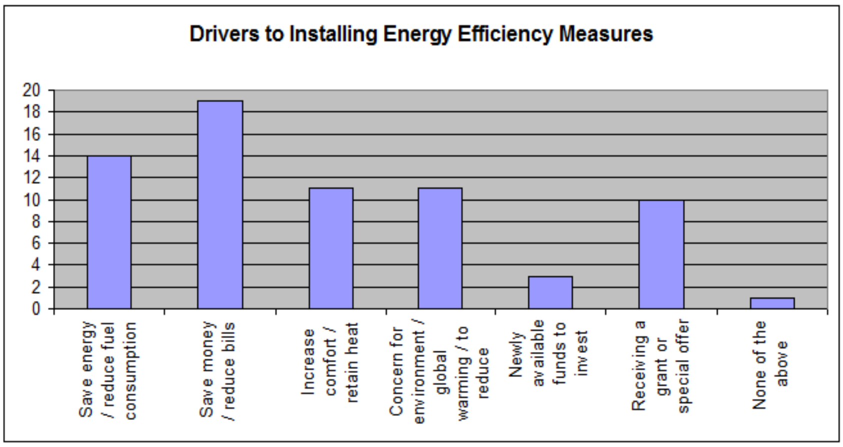

Figure 14: Drivers to adopting energy efficiency measures

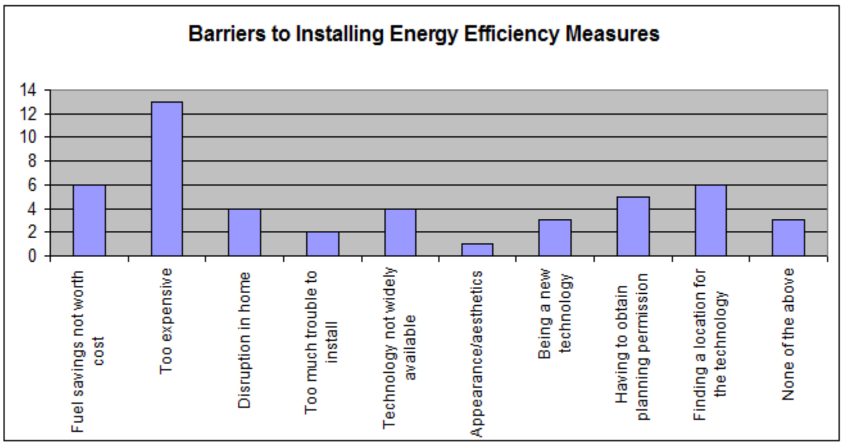

Figure 15: Barriers to adopting energy efficiency measures

Both the main driver and barrier to installing energy efficiency measures is cost (see figures 14 and 15). A significant 65% of respondents indicated that the main barrier was expense, followed by 30% who felt that the fuel savings were not worth the initial cost. However, a staggering 78% of people suggested that the main driver was to save money and reduce their fuel bill. There is perhaps a knowledge gap here whereby if people had more information about cost they might be more likely to consider adopting. Conversely, the least significant driver and barrier respectively were; newly available funds and aesthetics.

10.3 Correlation Analysis

A correlation analysis, included in Appendix E was run by combining questions into scalar variables. For example, responses to the attitudes questions (1 - 3) where averaged whilst ignoring unanswered questions per survey to obtain an attitude value. This meant reversing the scales for some questions which had negative attitudinal values such as: *"Reducing my households energy consumption would be inconvenient."*. The significant correlations found are described below:

- **Electricity Cost and Heating Cost:** the correlation of .825 with significance to 1% can be explained by the fact that households who are not conscious of their electricity consumption are also not conscious of their heating consumption, or are perhaps at home more and hence use both during the day.

- **Tenure and Knowledge:** the correlation of .707 can be attributed to the fact that the sample had a high proportion of students from Cranfield University who are mainly tenants and have good knowledge of the environment and energy.

- **Tenure and Age:** the negative correlation of -.584 between tenure and the average age of adults in the household can be attributed again to the fact that the sample had a high proportion of students living in rented accommodation.

- **Tenure and Efficiency:** the negative correlation of -.423 for tenure and dwelling efficiency, which was calculated from dwelling size and type suggests that tenants are more likely to live in less efficient houses, i.e. larger detached properties.

10.4 Regression Analysis and Reliability

The regression analysis to identify whether any of the 'shocks' defined in question 11 had an influence on energy consumption was unable to be performed due to the sample size and response rate, with only four respondents having moved house, two having a household member retire and one having a household member becoming unemployed. Cronbachs Alpha could also not be performed as the data set was too small once non-responses were considered. In order to obtain data on the groups more likely to have experienced these 'shocks' the survey could be distributed in locations which target shock groups such as baby groups.

10.5 Feedback

Participants were given the option to add feedback to the survey in order to make improvements on the format. Generally the responses showed that the survey was simple to complete and the wording clear, however at times lengthy, as was the table regarding energy efficiency measures in question 16. Perhaps this could be condensed into groups rather than individual measures. From a data entry perspective, the questions where the participant was required to circle a number on a scale were far more effective than when the participant was asked to fill in a table or add free text. Although it could be criticised as more restrictive using this method, the data is more accurate and easier to process, and the participant may also add comments throughout. Several respondents also added comments to better describe the changes to their heating patterns seasonally, hence a question to gather this data should also be included.

10.6 Limitations

The key failure of the pilot survey is the fact that the number of responses was inadequate to gain insight into the 'shocks' related questions that were to inform the model design process. This could be a result of question 11 having a time bound of the last year to prevent inaccuracy, however in future surveys the reference period for shocks could be extended to the last five years to obtain further data. Due to this, assumptions will need to be made until more detailed data becomes available. The main limitations were the small sample size and the high proportion of student respondents, thus making the sample unrepresentative of the general population.

Another key consideration for future surveys is the cost of printing, distributing and data processing. For an extensive sample the cost of conducting such a survey may prove impractical. In this case the model would have to rely on other data sources such as the UK Census.

11 Simple Model Example

The following chapter illustrates the modelling methodology described in chapter 7 by carrying out the process for a simple example. The model implemented below is purely demonstrative and not designed to give any scientific results.

11.1 Model Definition Using ODD Protocol

11.1.1 Overview

Purpose
The following model represents the decision-making process for adopting energy efficiency measures after retirement based on a potential loss of income. In reality there are many other factors to consider than just income, however since this model is just for demonstrative purposes the model has been kept as simple as possible.

Entities, State Variables and Scales
In this model the retired individual or household is the agent. The global effect of many retired individuals will lead to trends in the adoption of energy efficiency measures. Environment variables which affect all agents in the model are: energy price, retirement age, fuel poverty threshold and percentage population with a green attitude. The model runs with quarterly ticks, i.e. each tick represents a quarter of a year.

Process, Overview and Scheduling
The assumption and basis of the model is that as an individual retires they may see a sudden but predictable decrease in income [90]. The individual must then assess their energy requirements and the proportion of their new income that they spend on energy. This process occurs on each tick by fluctuating the energy price and hence each individual's state with respect to the new energy price.

11.1.2 Design Concepts

The objective of each agent is to avoid falling into fuel poverty where more than 10% of their income is spent on energy [6]. They can do this by either maintaining a high income or adopting energy efficiency measures. The agents cannot interact with each other, learn or predict but can sense changes in their environment such as fluctuations in energy price and choose to adapt to these changes by adopting. We expect to see an emergence of adoption behaviour as the cost of energy fluctuates.

The stochastic processes in the model are the household income which is generated randomly and an agent having a green attitude if a random number generated is less than the user input percentage of the population with a green attitude.

The observation parameters in this model are the percentage of the population in fuel poverty, the change in energy price and the number of adopters.

11.1.3 Details

Initialisation

The initial state of the model has the following parameter values: 100 household agents, a 10% income fuel poverty threshold, a retirement age of 65, and 10% of the population with a green attitude. The energy price begins at 1 and the initial percentage of the population in fuel poverty is obtained after each agent is assigned a percentage of income spent on energy.

Input data

The are no parameters in this model that rely on dynamic data hence there is no input data.

Submodels

The adoption decision submodel is defined by the individual assessing their energy requirements and the proportion of their income that they spend on energy. If the percentage that the individual spends on energy is greater or equal to the fuel poverty threshold (which will be a model parameter), the household then makes the decision whether to adopt a green technology (although not a specific type in this model), but they may only do this if they can afford the technology and have a green attitude. Once they adopt a technology they will return to the initial 'retired' state however the percentage of income spent on fuel will reduce due to adoption of the energy efficiency measures.

11.2 Conceptual Model in UML

Figure 16 represents a conceptual view of the model.

11.2(a) Data Requirements

There are no specific data requirements for this model due to its simplicity. More complex models may use an input parameter file to set up the initial state of the

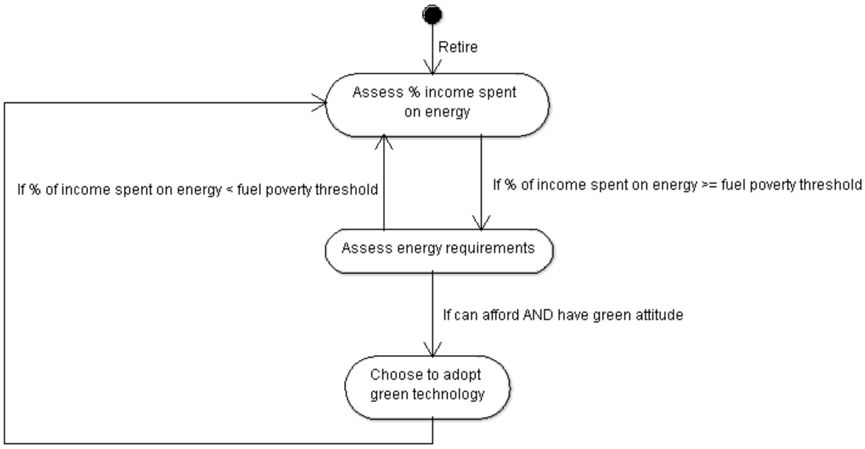

Figure 16: Conceptual UML model of retirement model

model. This would allow the model to be used for different data sets, for example, for modelling different geographical locations.

11.3 Model Implementation

The model is implemented in AnyLogic by creating an environment for all agents in one class and by defining individual agent actions in another. In the agent class the individual's actions are defined by a state chart which closely aligns with our conceptual model (figure 17).

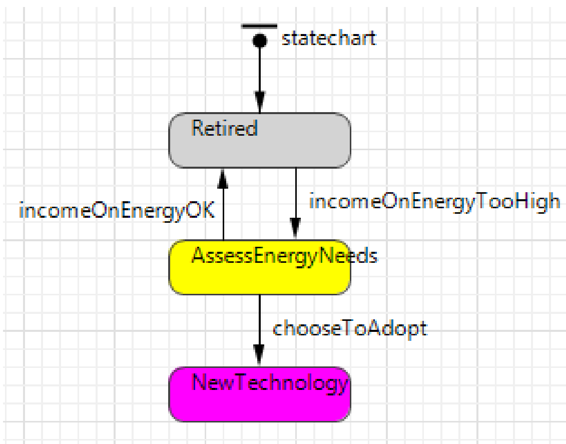

Figure 17: AnyLogic state chart of retirement model

Other variables included in the model are a randomly assigned economic factor which gives each household a different wealth such that only households which can afford to adopt new technology can, and green attitude which is assigned to a percentage of the population dependent on the initial parameter settings. Having a green attitude means the individual may choose to adopt a green technology.

11.4 Model Testing, Validation and Documentation

The model has not been tested, validated or documented due to the fact that it is purely for the purposes of demonstrating the method.

11.5 Analysis of Output Data

As stated previously, the model is not a scientific model hence the following analysis holds no real scientific value but gives an insight into using AnyLogic to implement the sort of model which has been defined in this project. Figure 18 shows the initial state of the model with the initial percentage of the population in fuel poverty at 11%. In the simulation, agents in the retired state are shown in grey, those in fuel poverty are shown in yellow and those with a green attitude have a green highlight.

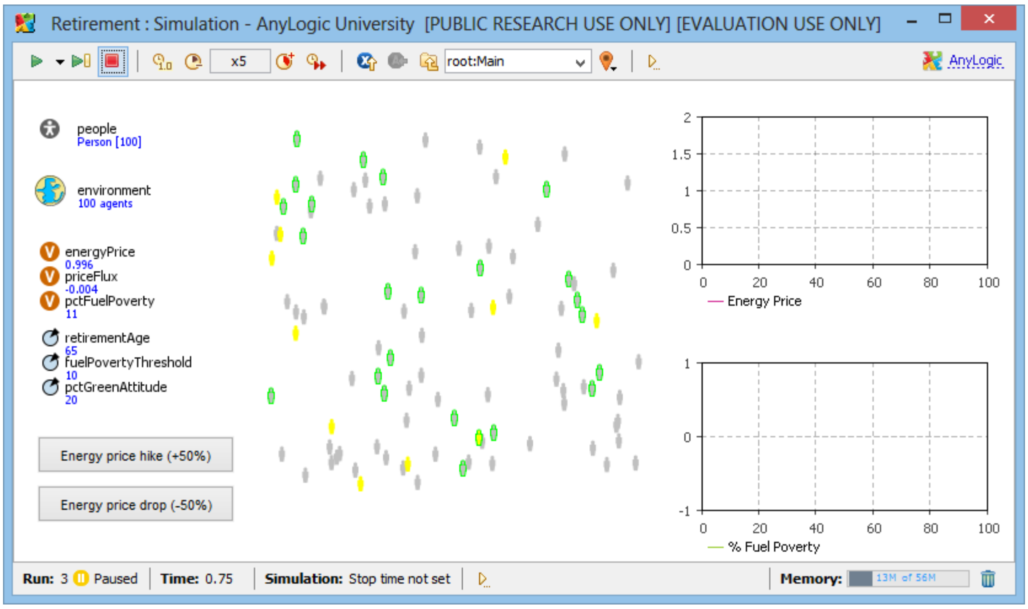

Figure 18: Initial state of retirement model

As the cost of energy increases reaching 1.08 (figure 19), the fuel poverty level of the population reaches 17%. At this point we can see that 3% of the population have satisfied the criteria to adopt green technology (pink).

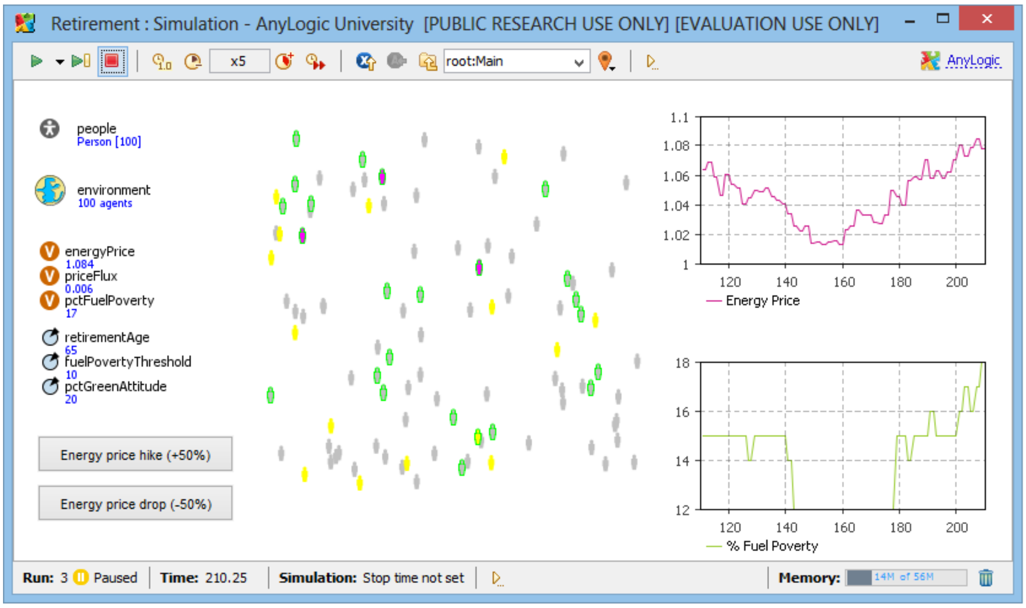

Figure 19: High energy price in retirement model

Later in the simulation when the energy price reduces to 0.96 (figure 20), the fuel poverty decreases to just 6% of the population and we can see a visible decrease in yellow individuals.

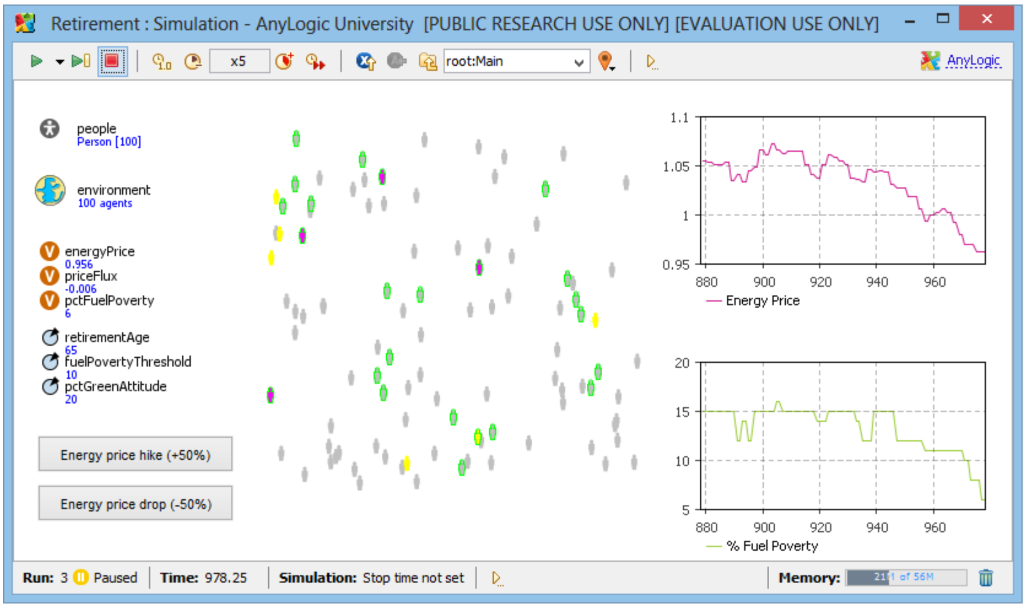

Figure 20: Low energy price in retirement model

Figures 21 and 22 show a 0.5 point increase and decrease in energy price respectively. It is clear that there are many more adopters when the price hikes with fuel poverty at 46% and when the price crunches the percentage of the population in fuel poverty reaches 0%.

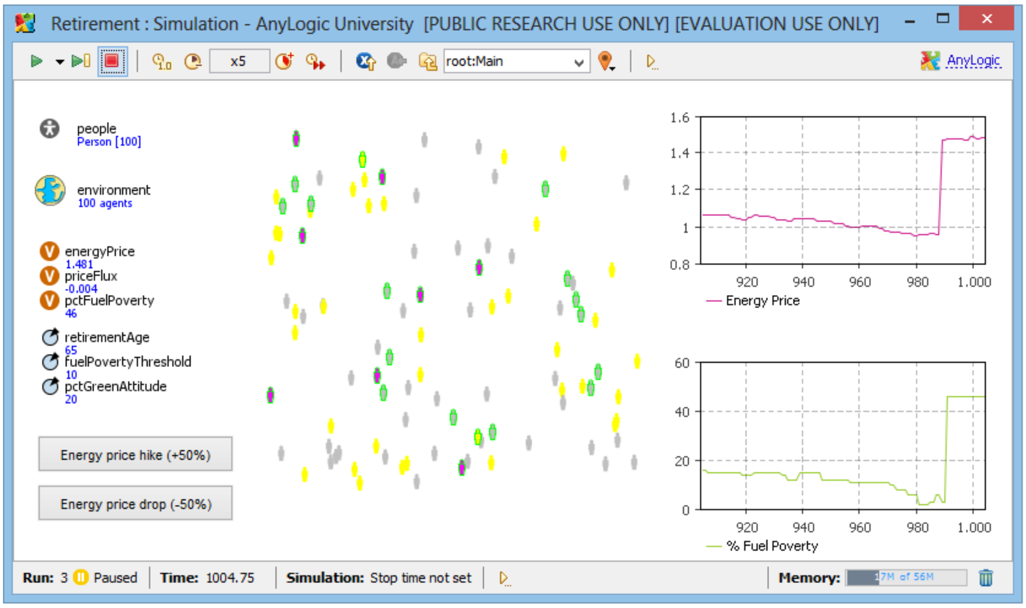

Figure 21: Energy price hike in retirement model

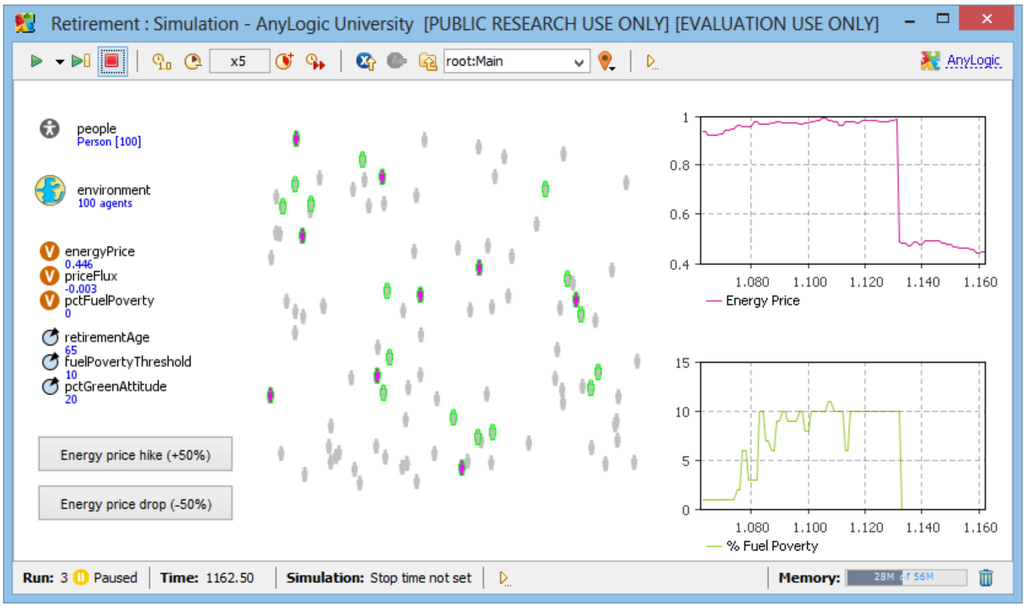

Figure 22: Energy price crunch in retirement model

Although not a scientific model, hopefully this simple example has shown how the software can be used and that AnyLogic is a suitable tool for this purpose.

12 Conclusion

A review of current literature showed a lack of comprehensive domestic energy system models both granular enough to consider occupant behaviour and dwelling construction. The models which do consider this field do not consider the effect of household life-stage changes such as retirement and moving house. A model schema to bridge this gap has been put forward in this work, with agent-based modelling selected as the suitable paradigm due to its bottom-up approach and ability to represent individual entities within a system with their own goals, and such that through their interactions with each other and their environment, emergent behaviours may be observed. Significant model parameters were identified from the literature as key factors affecting domestic energy consumption. These were then included in the model, which was designed using the ODD protocol. A method to ensure valid model implementation was suggested and executed using a simple example for reference. The model schema was limited in complexity for the first iteration such that it is implementable and emergent behaviour is not abstracted by an excess of model outputs. After identifying that agent-based models are data-intensive, a pilot survey was conducted in order to gather data to inform the model relationships, especially those of household 'shocks' since this is less well documented in the literature. Due to a small sample size which was biased towards highly educated students and staff, the results were found to be unrepresentative of the general population and suggestions were given in order to improve the survey for future iterations, including targeting groups with a high proportion of households who fall into one or more of the 'shock' categories.

A limitation of this work is the fact that the pilot survey provided no results on the specified household 'shock' categories. As a result assumptions of how these relationships should be implemented in the model had to be made based on limited literature sources. To correct this, a modified survey could be distributed to a wider sample in order to gain new insight.

12.1 Further Work

As has been stated previously, the first version of the model schema defined here has been restricted in order to reduce its complexity such that it is realistically implementable, and that any added level of complexity does not abstract potential emergent behaviour that may be observed. Once the method defined in section 7 has been executed, including full validation and testing, enhancements may be added in order to increase the complexity.

Suggestions for improvements are given below, the model could consider:

- changes to government policy
- variations in work and working from home patterns
- networks of friends and family can be added as connections as well as proximity
- a representation of the relationship between high demand and cost of a product with respect to the adoption of energy efficiency measures
- seasonal weather data and hence heating pattern changes
- changes to dwelling stock as properties age and are demolished and new more efficient properties are constructed.

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A Ethics Approval

Katherine Stonebridge

From:	SEREC
Sent:	26 September 2013 09:17
To:	Wood, Katherine
Cc:	Varga, Liz
Subject:	Ethics Proposal 092-2013
Importance:	High

Dear Katherine

I have now heard that your proposed research activity "Household Energy Survey" has been confirmed by SEREC as posing a low risk in terms of research ethics. You can now proceed with the research activities you have sought approval for and we wish you a successful project.

Please remember that SEREC occasionally conducts audits of low risk projects and we may therefore contact you during or following execution of your fieldwork to verify that you are following good practice.

Guidance on good practice is available at:
https://intranet.cranfield.ac.uk/researchethics/Pages/SEREC.aspx

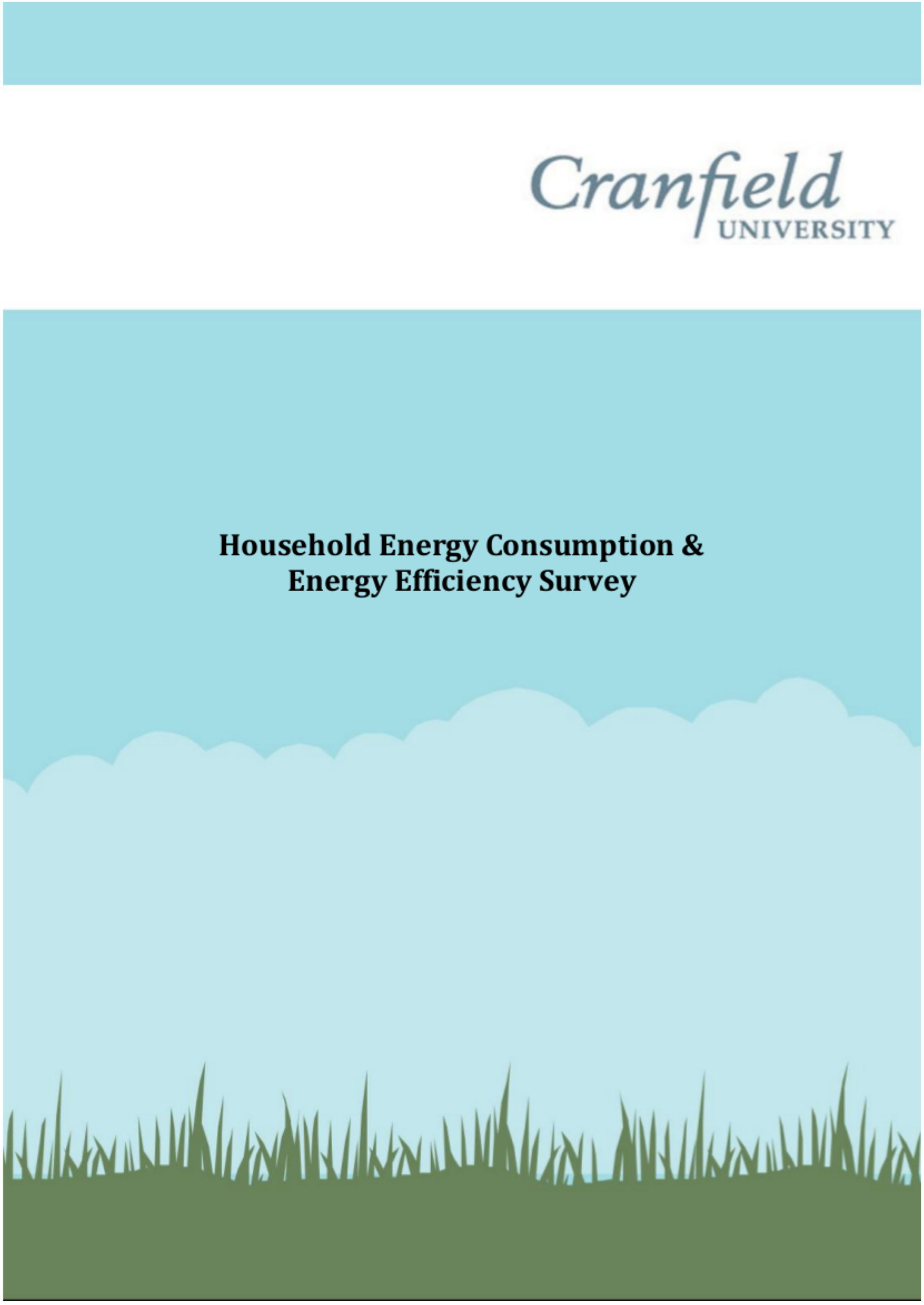
With best regards

Sue

Sue Garrod
Departmental Secretary
Department of Integrated Systems
School of Engineering
01234 754165

B Pilot Survey

B.1 Front Cover



B.2 Introduction

Dear Participant,

This is a pilot survey which will collect information on household energy consumption from various areas in Peterborough city. It aims to assess some of your views towards individual household energy consumption and should take no longer than 15 minutes of your time.

Your participation is voluntary and greatly appreciated. All information collected will be treated in confidence and be held securely at Cranfield University and City College Peterborough in accordance with the Data Protection Act 1998. The anonymised results will be summarised and no individual household information will be used.

At the end of the survey there is space for your comments and suggestions as to how this survey could be improved before distribution. Please be as candid and honest as you can since your opinions will help to make the results gained from this survey more accurate.

Thank you for your participation.

Katherine Wood
Postgraduate student (PhD)
E-mail: k.wood@cranfield.ac.uk
School of Engineering,
Cranfield University.

B.3 Section 1: Environmental Beliefs and Values

Section 1: ENVIRONMENTAL BELIEFS & VALUES

Question 1: We all value the environment in different ways. Which of the following statements best describes your view? (Please tick one)

☐	The highest priority should be given to economic considerations, even if it hurts the environment.
☐	Both the economy and the environment are important, but the economy should come first.
☐	The economy and the environment are equally important.
☐	Both the environment and the economy are important, but the environment should come first.
☐	The highest priority should be given to protecting the environment, even if it hurts the economy.

Question 2: Please rate your knowledge of the following topics.

	No Knowledge	Little Knowledge	Moderate Knowledge	Good knowledge	Expert Knowledge
Greenhouse gas emissions from household energy consumption.	☐	☐	☐	☐	☐
Energy saving in the home.	☐	☐	☐	☐	☐
Depletion of fossil fuel reserves.	☐	☐	☐	☐	☐
The Government's Green Deal.	☐	☐	☐	☐	☐

Question 3: For each statement, please tick the option which most closely matches your own opinion.

	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
During the past year I have done at least three things to reduce my household's energy consumption.	☐	☐	☐	☐	☐
It would save me money to reduce my household's energy consumption.	☐	☐	☐	☐	☐
Reducing my household's energy consumption would be inconvenient.	☐	☐	☐	☐	☐
I choose to buy energy efficient equipment to reduce my energy consumption.	☐	☐	☐	☐	☐
Price is more important than energy efficiency when buying new appliances.	☐	☐	☐	☐	☐
I know I need to change my habits and attitudes to reduce my household energy consumption.	☐	☐	☐	☐	☐

B.4 Section 2: Building Characteristics and Section 3: Home Energy Use

Section 2: BUILDING CHARACTERISTICS

Question 4: What type of building do you live in? (Please tick one)

- ☐ Converted flat
- ☐ Purpose-built flat
- ☐ Detached house
- ☐ Semi-detached house
- ☐ End of terrace house
- ☐ Terraced house
- ☐ Semi-detached bungalow
- ☐ Detached bungalow
- ☐ Other (specify)……………………………….

Question 5: How many heated rooms are there in your property, including bathrooms and toilets? (Please tick one)

- ☐ 1 - 3 rooms
- ☐ 4 – 6 rooms
- ☐ 7 - 9 rooms
- ☐ 10 - 12 rooms
- ☐ 13 - 15 rooms
- ☐ 16+ rooms

Question 6: What is the energy efficiency rating (EPC) of your property? (Please tick one)

- ☐ A
- ☐ B
- ☐ C
- ☐ D
- ☐ E
- ☐ F
- ☐ G
- ☐ I don't know

Section 3: HOME ENERGY USE

Question 7: What temperature do you set your home (or main living room) thermostat to in winter? (Please tick one)

- ☐ 16°C or less
- ☐ 17°C - 19°C
- ☐ 20°C - 22°C
- ☐ 23°C or higher
- ☐ I don't know
- ☐ I don't have a thermostat

Question 8: Averaged over the whole year, how much do you usually pay for energy?

My **electricity** bill costs: £…………………………… ☐ I don't know how much my electricity bill costs.
PER
☐ Month ☐ Quarter ☐ Year ☐ By pre-payment meter ☐ Other (specify)…………………….

My **heating** or **fuel** bill costs: £…………………… ☐ I don't know how much my heating/fuel bill costs.
PER
☐ Month ☐ Quarter ☐ Year ☐ By pre-payment meter ☐ Other (specify)…………………….

OR

My **combined** bill costs: £…………………………… ☐ I don't know how much my combined bill costs.
PER
☐ Month ☐ Quarter ☐ Year ☐ By pre-payment meter ☐ Other (specify)…………………….

B.5 Section 4: Appliance Usage and Section 5: Significant Household Changes

Section 4: APPLIANCE USAGE

Question 9: In a normal week, when do you have your heating and/or appliances switched on (e.g. your television, oven etc.)?

Time of day		Mon	Tues	Wed	Thurs	Fri	Sat	Sun
Early morning	**6am - 8:59am**	☐	☐	☐	☐	☐	☐	☐
Mid morning	**9am - 11:59am**	☐	☐	☐	☐	☐	☐	☐
Early afternoon	**12pm - 2:59pm**	☐	☐	☐	☐	☐	☐	☐
Mid afternoon	**3pm - 5:59pm**	☐	☐	☐	☐	☐	☐	☐
Early evening	**6pm - 8:59pm**	☐	☐	☐	☐	☐	☐	☐
Evening	**9pm - 11:59pm**	☐	☐	☐	☐	☐	☐	☐
Night	**12am - 5:59am**	☐	☐	☐	☐	☐	☐	☐

Question 10: Does anyone in your household work from home? If so, please select the number of days per week?

☐ 1 day ☐ 2 days ☐ 3 days ☐ 4 days ☐ 5 days ☐ 6+ days

Section 5: SIGNIFICANT HOUSEHOLD CHANGES

Question 11: In the last year has your household undergone any of the following significant changes?

☐ I have a new baby in my household.	
☐ I have moved house.	
Is your new property smaller, larger or the same size as your last property?	☐ Smaller ☐ Larger ☐ Same size
Is your new property less, more or as energy efficient as your last property?	☐ Less energy efficient ☐ More energy efficient ☐ As energy efficient
Was energy efficiency an important consideration when purchasing your home?	☐ Yes ☐ To some extent ☐ No
☐ I or someone in my household has retired.	
☐ I or someone in my household has become unemployed or given up work.	
☐ My household's size has reduced, e.g. child gone to university, bereavement, divorce.	
☐ None of the above. **GO TO Q15.**	

B.6 Section 5 (cont.): Significant Household Changes

<u>Question 12:</u> As a result of this/these change(s) to your household, have you seen any difference in your energy consumption (by comparing each bill with the same period last year)?

- ☐ Yes — **GO TO NEXT QUESTION.**
- ☐ No — **GO TO Q14.**
- ☐ I don't know — **GO TO Q15.**

<u>Question 13:</u> If you answered YES to the last question, did your energy consumption increase or decrease and by how much?

My **electricity** bill	☐ increased ☐ decreased	**by £.................... *PER***	☐ Week ☐ Month ☐ Other (specify)................................	☐ Quarter ☐ Year
My **heating** or **fuel** bill	☐ increased ☐ decreased	**by £.................... *PER***	☐ Week ☐ Month ☐ Other (specify)................................	☐ Quarter ☐ Year
OR				
My **combined** bill	☐ increased ☐ decreased	**by £.................... *PER***	☐ Week ☐ Month ☐ Other (specify)................................	☐ Quarter ☐ Year

Please explain why you think this might be:

....

....

....

....

<u>Question 14:</u> Did you make any changes to the energy usage of your household as <u>a result of your significant change(s)</u> stated previously (such as changing your behaviour or installing energy efficiency measures)? Please explain:

....

....

....

....

B.7 Section 6: Energy Efficiency Measures

Section 6: ENERGY EFFICIENCY MEASURES

Question 15: Do you think there is enough information accessible on the types of energy efficiency measures and green technology available to install in your home (e.g. potential costs and benefits), to make informed choices about installing them?

☐ Yes ☐ No ☐ I don't know

Question 16: Would you be open to or have you installed any energy efficiency or green technology measures? If so, please select from the list.

Energy Efficiency Measures	Would not install	Would need more information	Would install	Already installed without Green Deal	Already installed with Green Deal
Heat pump (air/ground/water source)	☐	☐	☐	☐	☐
Biomass boiler/heater	☐	☐	☐	☐	☐
Cavity/internal wall insulation	☐	☐	☐	☐	☐
Loft/roof insulation	☐	☐	☐	☐	☐
Draught proofing	☐	☐	☐	☐	☐
Efficient hot water system	☐	☐	☐	☐	☐
External wall insulation	☐	☐	☐	☐	☐
Heating, air-conditioning, hot water, or lighting controls	☐	☐	☐	☐	☐
Micro wind generation (domestic wind turbine)	☐	☐	☐	☐	☐
Photovoltaics (solar panels)	☐	☐	☐	☐	☐
Energy efficient boiler	☐	☐	☐	☐	☐
Micro combined heat and power	☐	☐	☐	☐	☐
Flue gas heat recovery devices	☐	☐	☐	☐	☐
High performance external doors	☐	☐	☐	☐	☐
Hot water cylinder/pipework/duct insulation	☐	☐	☐	☐	☐
Mechanical ventilation with heat recovery	☐	☐	☐	☐	☐
Secondary/replacement glazing	☐	☐	☐	☐	☐
Solar water heating	☐	☐	☐	☐	☐
Solar blinds, shutters and shading devices	☐	☐	☐	☐	☐
Under-floor heating/insulation	☐	☐	☐	☐	☐
Wood stove/boiler	☐	☐	☐	☐	☐
Energy efficient lighting	☐	☐	☐	☐	☐
Other (specify).................................	☐	☐	☐	☐	☐
Other (specify).................................	☐	☐	☐	☐	☐
Other (specify).................................	☐	☐	☐	☐	☐

B.8 Section 7: Household Characteristics

Question 17: What are the main barriers that would affect your decision to install energy efficiency or green technology measures?

- ☐ Fuel savings not worth cost
- ☐ Too expensive
- ☐ Disruption in home
- ☐ Too much trouble to install
- ☐ Technology not widely available
- ☐ Appearance / aesthetics
- ☐ Being a new technology
- ☐ Having to obtain planning permission
- ☐ Finding a location for the technology
- ☐ None of the above

Question 18: What are the main drivers that would affect your decision to install energy efficiency or green technology measures?

- ☐ Save energy / reduce fuel consumption
- ☐ Save money / reduce bills
- ☐ Increase comfort / retain heat
- ☐ Concern for environment / global warming / to reduce emissions
- ☐ Newly available funds to invest
- ☐ Receiving a grant or special offer
- ☐ None of the above

Question 19: Would any of the following changes to your household influence your decision to install energy efficiency or green technology measures?

- ☐ Having a baby.
- ☐ Moving house.
- ☐ I or someone in my household retiring.
- ☐ I or someone in my household becoming unemployed or giving up work.
- ☐ My household size reducing, e.g. child going to university, bereavement, divorce.
- ☐ None of the above.

Section 7: HOUSEHOLD DEMOGRAPHIC CHARACTERISTICS

Question 20: Are you the homeowner or tenant of your property?

- ☐ Homeowner
- ☐ Tenant

Question 21: Which of the following best describes your household? (Please tick one)

- ☐ Couple with no children
- ☐ Couple with children
- ☐ Single parent with children
- ☐ House-share
- ☐ Single person household
- ☐ Other (e.g. extended family) (specify)

……………………………………………………………

B.9 Section 7 (cont.): Household Characteristics

Question 22: What is your household's TOTAL income per year before tax? (Please tick one)

- ☐ Less than £10 000
- ☐ £10 000 - £19 999
- ☐ £20 000 - £29 999
- ☐ £30 000 - £39 999
- ☐ £40 000 - £49 999
- ☐ £50 000 - £69 999
- ☐ £70 000 - £99 999
- ☐ £100 000 or more

Question 23: Please describe all of the ADULT members of your household (including children 18 and over):

Me:

Age	☐ 18-25 ☐ 26-35 ☐ 36-45 ☐ 46-55	☐ 56-65 ☐ 66-75	☐ 76-85 ☐ 86+
Employment status	☐ Full-time ☐ Unemployed ☐ Full-time student	☐ Part-time ☐ Retired/Pension recipient ☐ Part-time student	☐ Self-employed/Casual ☐ Home duties
Current occupation	☐ Manager, director or senior official ☐ Skilled trades occupation ☐ Sales/customer service occupation ☐ Other (specify)..	☐ Administrative or secretarial occupation ☐ Technical occupation ☐ Process, plant or machine operative	☐ Professional occupation ☐ Caring, leisure, other service occupation ☐ Elementary occupation (e.g. facilities, cleaner) ☐ N/A

Adult 2:

Age	☐ 18-25 ☐ 26-35 ☐ 36-45 ☐ 46-55	☐ 56-65 ☐ 66-75	☐ 76-85 ☐ 86+
Employment status	☐ Full-time ☐ Unemployed ☐ Full-time student	☐ Part-time ☐ Retired/Pension recipient ☐ Part-time student	☐ Self-employed/Casual ☐ Home duties
Current occupation	☐ Manager, director or senior official ☐ Skilled trades occupation ☐ Sales/customer service occupation ☐ Other (specify)..	☐ Administrative or secretarial occupation ☐ Technical occupation ☐ Process, plant or machine operative	☐ Professional occupation ☐ Caring, leisure, other service occupation ☐ Elementary occupation (e.g. facilities, cleaner) ☐ N/A

Adult 3:

Age	☐ 18-25 ☐ 26-35 ☐ 36-45 ☐ 46-55	☐ 56-65 ☐ 66-75	☐ 76-85 ☐ 86+
Employment status	☐ Full-time ☐ Unemployed ☐ Full-time student	☐ Part-time ☐ Retired/Pension recipient ☐ Part-time student	☐ Self-employed/Casual ☐ Home duties
Current occupation	☐ Manager, director or senior official ☐ Skilled trades occupation ☐ Sales/customer service occupation ☐ Other (specify)..	☐ Administrative or secretarial occupation ☐ Technical occupation ☐ Process, plant or machine operative	☐ Professional occupation ☐ Caring, leisure, other service occupation ☐ Elementary occupation (e.g. facilities, cleaner) ☐ N/A

B.10 Section 7 (cont.): Household Characteristics

Adult 4:

Age	☐ 18-25	☐ 26-35	☐ 36-45	☐ 46-55	☐ 56-65	☐ 66-75	☐ 76-85	☐ 86+

Employment status	☐ Full-time ☐ Unemployed ☐ Full-time student	☐ Part-time ☐ Retired/Pension recipient ☐ Part-time student	☐ Self-employed/Casual ☐ Home duties
Current occupation	☐ Manager, director or senior official ☐ Skilled trades occupation ☐ Sales/customer service occupation ☐ Other (specify)..	☐ Administrative or secretarial occupation ☐ Technical occupation ☐ Process, plant or machine operative	☐ Professional occupation ☐ Caring, leisure, other service occupation ☐ Elementary occupation (e.g. facilities, cleaner) ☐ N/A

Adult 5:

Age	☐ 18-25	☐ 26-35	☐ 36-45	☐ 46-55	☐ 56-65	☐ 66-75	☐ 76-85	☐ 86+

Employment status	☐ Full-time ☐ Unemployed ☐ Full-time student	☐ Part-time ☐ Retired/Pension recipient ☐ Part-time student	☐ Self-employed/Casual ☐ Home duties
Current occupation	☐ Manager, director or senior official ☐ Skilled trades occupation ☐ Sales/customer service occupation ☐ Other (specify)..	☐ Administrative or secretarial occupation ☐ Technical occupation ☐ Process, plant or machine operative	☐ Professional occupation ☐ Caring, leisure, other service occupation ☐ Elementary occupation (e.g. facilities, cleaner) ☐ N/A

Adult 6:

Age	☐ 18-25	☐ 26-35	☐ 36-45	☐ 46-55	☐ 56-65	☐ 66-75	☐ 76-85	☐ 86+

Employment status	☐ Full-time ☐ Unemployed ☐ Full-time student	☐ Part-time ☐ Retired/Pension recipient ☐ Part-time student	☐ Self-employed/Casual ☐ Home duties
Current occupation	☐ Manager, director or senior official ☐ Skilled trades occupation ☐ Sales/customer service occupation ☐ Other (specify)..	☐ Administrative or secretarial occupation ☐ Technical occupation ☐ Process, plant or machine operative	☐ Professional occupation ☐ Caring, leisure, other service occupation ☐ Elementary occupation (e.g. facilities, cleaner) ☐ N/A

Question 24: As children grow up, your household will use different amounts of energy. So we can better understand this pattern, please specify how many children in your household are in each age band.

Number of children aged between **0 - 4** in your household:
Number of children aged between **5 - 12** in your household:
Number of children aged between **13 - 17** in your household:

B.11 Section 7 (cont.): Household Characteristics

<u>Question 25:</u> For the purposes of defining urban and rural trends, please could you provide the <u>first part of</u> your postcode?

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<u>FEEDBACK:</u> Thank you for your time and participation in this pilot survey. In order to improve the survey before distribution please use the following space to highlight any issues or improvements to be considered.

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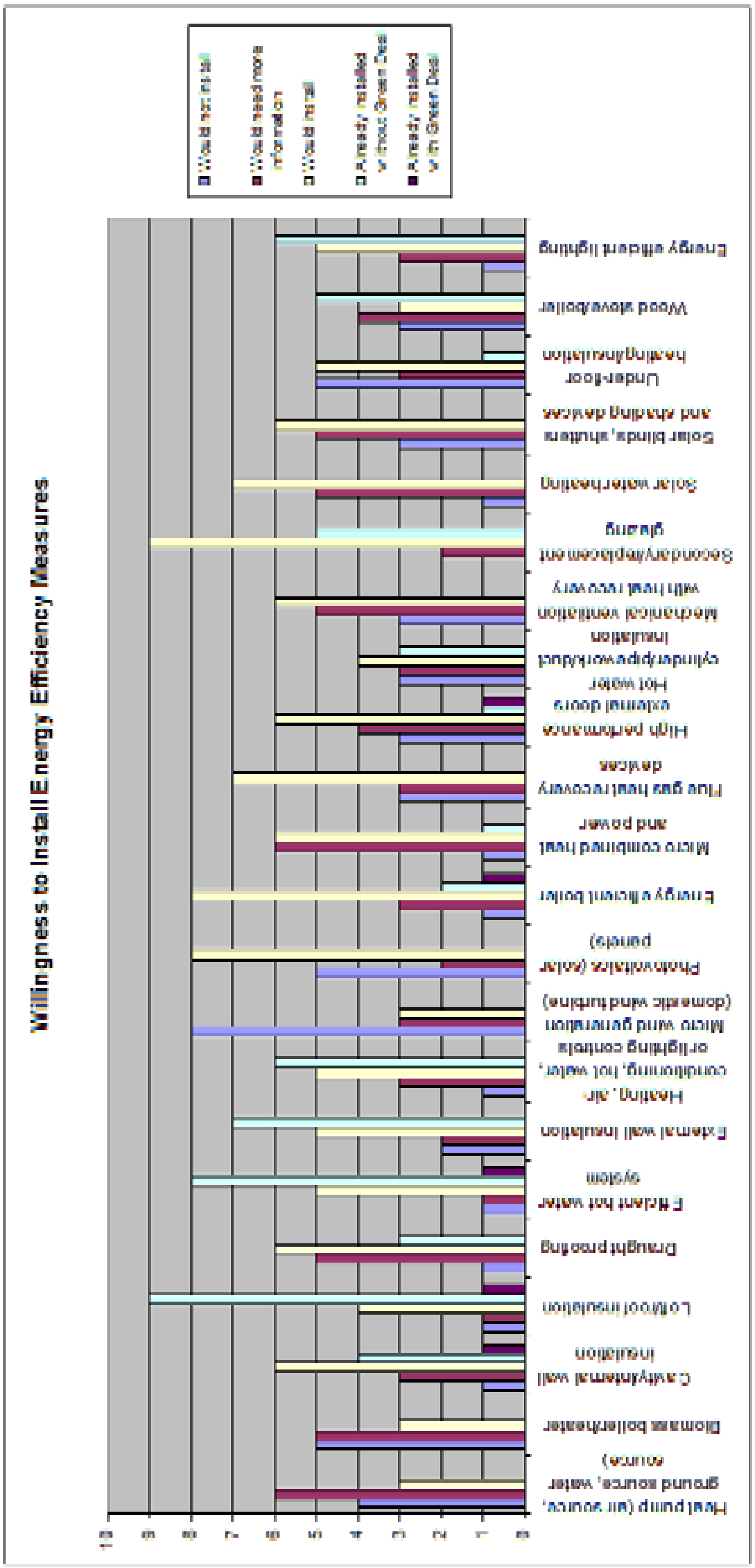
Thank you for your participation.

C Table of Interactions Between Energy Consumption Variables

	Attitude	Knowledge	Gender	Dwelling Age	Number of Appls.	Electricity Consump.	Gas Consump.	Dwelling Type	Dwelling Size	Household Type	Family Life Stage	Number of Children	Income	Home During Day	Internal Temp.	Energy-Saving Appls.	Peer Network	Cost of Energy	Tenure
Attitude																			
Knowledge																			
Gender																			
Dwelling Age																			
Number of Appls.																			
Electricity Consump.	Most influenced by conservation attitudes rather than demographics [17].			Consumption higher in modern houses due to more appliances [9].	More appliances lead to greater consumption [9].														
Gas Consump.			Slight increase in gas consumption for female-headed households [9].	Greater gas consumption in older houses, up to 65% variance [9].															
Dwelling Type							Detached/semi-detached use more energy due to exposed surfaces and larger size. [9].												
Dwelling Size							Larger houses use more energy due to heat loss [22].												
Household Type						Couples with children use much more electricity and single people use much less [9].	Couples with children use slightly more gas (economy of scale) [9]												
Family Life Stage					Couples with teenage children use more appliances [9].	Couples with children use much more electricity and single people use much less [9].	Couples with children use slightly more gas (economy of scale). Elderly use more energy but less pp [9].												
Number of Children					Children use more electrical appliances and this increases with age [9].	Significant increase in electricity consumption with more children [9].	Slight increase in gas consumption with more children (economy of scale) [9].												
Income			Average male earnings greater than female. Consider impact in same-gender households [80].		Increase in the number of appliances linked to higher disposable income [6].	Electricity consumption increases with wealth. More prevalent than for gas [9].	Gas consumption increases with wealth. Not as much as electricity as economy of scale [9].		Higher income linked to larger house and greater space heating [10].	Elderly generally have lower income but spend more time at home hence spend more of their income on energy [13].									

Home During Day						Working from home increases consumption e.g. lighting [12].	Working from home increases consumption e.g. heating [12].			Generally families with children are not at home during the day [10]. Elderly spend more time at home [13].			Elderly generally have lower income but spend more time at home hence spend more of their income on energy [13].						
Internal Temp.							Greater internal temperature increases gas consumption.				Elderly tend to have higher comfort requirements [9].		As income increases so does thermal comfort [10].						
Energy-Saving Appls.	DEFRA study showed 71% of respondents looked for energy saving logo when purchasing appliances [62].					Energy efficient appliances lead to reduced energy consumption [61].	Energy efficient boilers and heating systems lead to reduced gas consumption [74].						Lower income households don't have access to funds to buy tech which would reduce their bills [11].						
Peer Network						Reduced when access to peer consumption data was shared between participants [18].													
Cost of Energy						Adaptation to small price increases but larger increases lead to decreased demand [23].	Adaptation to small price increases but larger increases lead to decreased demand [23].												
Tenure						Owner occupied homes use far more energy, but electricity usage is higher in rental properties as more do not have gas [22].	Owner occupied homes use far more energy, but electricity usage is higher in rental properties as more do not have gas [22].												
Willingness to adopt		Those who seek information are far more likely to adopt [30].														For a household if utility outweighs the barriers then adoption [32].	Word of mouth and visual technology presence increases adoption [30-32].	When potential savings are greater adoption more likely [36].	Rental properties less able to adopt as can't alter property [32,36].

D Graph of Pilot Survey Willingness to Adopt



E Table of Pilot Survey Correlations

Correlations

		ELEC_COST	HEATING_COST	COMBINED_COST	DWELLING_EFFICIENCY	TENURE	INTERNAL_TEMP	HEATING_FREQ	Q22_INCOME	HOUSEHOLD_AVG_AGE	ATTITUDES_1	KNOWLEDGE	NUM_CHILDREN
ELEC_COST	Pearson Correlation	1	.825**	.b	.497	.010	-.006	-.552	.291	-.008	-.050	.086	.b
	Sig. (2-tailed)		.006		.144	.978	.987	.098	.415	.982	.892	.814	0.000
	N	10	9	1	10	10	9	10	10	10	10	10	3
HEATING_COST	Pearson Correlation	.825**	1	.b	.535	-.157	.112	-.540	.187	-.137	-.291	-.160	.b
	Sig. (2-tailed)	.006			.111	.665	.774	.107	.606	.706	.415	.659	
	N	9	10	1	10	10	9	10	10	10	10	10	2
COMBINED_COST	Pearson Correlation	.b	.b	1	.910	-.814	.b	-.814	.959	-.724	-.415	-.943	.b
	Sig. (2-tailed)				.272	.394		.394	.182	.485	.728	.215	
	N	1	1	3	3	3	1	3	3	3	3	3	1
DWELLING_EFFICIENCY	Pearson Correlation	.497	.535	.910	1	-.423*	.113	-.046	-.020	.326	.047	-.381	-.168
	Sig. (2-tailed)	.144	.111	.272		.044	.656	.840	.934	.139	.836	.073	.718
	N	10	10	3	23	23	18	22	19	22	22	23	7
TENURE	Pearson Correlation	.010	-.157	-.814	-.423*	1	.000	-.090	-.171	-.584**	.211	.756**	.036
	Sig. (2-tailed)	.978	.665	.394	.044		1.000	.690	.484	.004	.345	.000	.940
	N	10	10	3	23	23	18	22	19	22	22	23	7
INTERNAL_TEMP	Pearson Correlation	-.006	.112	.b	.113	.000	1	.339	-.203	-.209	-.010	-.114	.b
	Sig. (2-tailed)	.987	.774		.656	1.000		.184	.451	.405	.969	.651	0.000
	N	9	9	1	18	18	19	17	16	18	18	18	5
HEATING_FREQ	Pearson Correlation	-.552	-.540	-.814	-.046	-.090	.339	1	-.248	-.037	.082	-.090	-.540
	Sig. (2-tailed)	.098	.107	.394	.840	.690	.184		.307	.873	.724	.689	.269
	N	10	10	3	22	22	17	22	19	21	21	22	6
INCOME	Pearson Correlation	.291	.187	.959	-.020	-.171	-.203	-.248	1	.050	.081	-.082	.752
	Sig. (2-tailed)	.415	.606	.182	.934	.484	.451	.307		.838	.740	.739	.085
	N	10	10	3	19	19	16	19	19	19	19	19	6
HOUSEHOLD_AVG_AGE	Pearson Correlation	-.008	-.137	-.724	.326	-.584**	-.209	-.037	.050	1	-.218	-.326	-.320
	Sig. (2-tailed)	.982	.706	.485	.139	.004	.405	.873	.838		.342	.139	.485
	N	10	10	3	22	22	18	21	19	22	21	22	7
ATTITUDES_1	Pearson Correlation	-.050	-.291	-.415	.047	.211	-.010	.082	.081	-.218	1	.357	-.431
	Sig. (2-tailed)	.892	.415	.728	.836	.345	.969	.724	.740	.342		.103	.335
	N	10	10	3	22	22	18	21	19	21	22	22	7
KNOWLEDGE	Pearson Correlation	.086	-.160	-.943	-.381	.756**	-.114	-.090	-.082	-.326	.357	1	.317
	Sig. (2-tailed)	.814	.659	.215	.073	.000	.651	.689	.739	.139	.103		.488
	N	10	10	3	23	23	18	22	19	22	22	23	7
NUM_CHILDREN	Pearson Correlation	.b	.b	.b	-.168	.036	.b	-.540	.752	-.320	-.431	.317	1
	Sig. (2-tailed)	0.000			.718	.940	0.000	.269	.085	.485	.335	.488	
	N	3	2	1	7	7	5	6	6	7	7	7	7

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

b. Cannot be computed because at least one of the variables is constant.